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EXPANSION AND IMPROVEMENT OF SKF COMPUTER PROGRAM SHABERTH
A COMPUTER PROGRAM SHABERTH STEADY STATE AND TRANSIENT THERMAL ANALYSIS OF A SHAFT BEARING SYSTEM

RESEARCH LABORATORY
SKF INDUSTRIES, INC. 389746
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KING OF PRUSSIA, PA.

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AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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Publication of this report does not constitute Air Force approval of the reports findings or conclusions. It is published only for the exchange and stimulation of ideas.

This report describes the work performed by SKF Industries, Inc. at its Technology Center in King of Prussia, Pa. for the United States Air Force Systems Command, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio and for the Naval Air Propulsion Test Center, Trenton, N. J. The work was performed over a seven month period starting in February 1976 under U. S. Air Force Contract No. F33615-76-C-2061 and Navy MIPR No. M52376-3-000007. Mr. John Schrand administered the project for the Air Force and Mr. Raymond Valori administered the project for the Navy.

Place

The project was conducted at SKF under the direction of Messrs. P. S. Given and T. E. Tallian. The SKF report designation is No. AL76P032.

This report contains documentation of the enhancements made to SKF Computer Program SHABERTH and the results of the SHABERTH analysis of two shaft bearing systems.

This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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This report contains documentation of the enhancements made to SKF Computer Program SHABERTH, an analytical computer program for the study of steady state and transient thermal performance of rolling element bearings and flexible shaft systems.

The full friction solution for ball and roller bearings subjected to general axial, radial and moment loading was implemented. Provision was made to include the affects of user specified ring → next page

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and rolling element material properties.

Nonlinear equation solution schemes were examined. The scheme within SHABERTH was tested and improved.

SHABERTH was used to model the performance of two distinct shaft bearing systems using optional levels of complexity. Results from the analyses are presented.

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NOMENCLATURE

$\{A\}$	A vector of constants used in the Fletcher Powell Method
$[A]$	Matrix used in the Fletcher Powell Method
$[B]$	Matrix used in the Fletcher Powell Method
D	Ball or roller diameter (in. or mm)
d_m	Bearing pitch diameter (in. or mm)
$\{E\}$	Scale vector used in the Powell Method
Eq_j	The numerical value of the nonlinear equation j, $Eq_j = (X_i)$, evaluated at a specific set of x_i, $i = 1,N$
$[F]$	The inverse of the matrix of the second order partial derivatives of ϕ with respect to $\{X\}$
f_i	A vector of damping factors $0. > f_i \geq 1$
$\{G\}$	The gradient vector of the partials of ϕ with respect to the components of $\{X\}$
$[H]$	The matrix, the elements of which are the second order partial derivatives of ϕ, with respect to the variables $\{X\}$
J	Ball moment of inertia in-lb sec^2
(K)	Iteration index
$[M]$	The Jacobian matrix with elements $\partial\phi_i / \partial X_i$
Mg_z	Ball gyroscopic moment about the z axis (in - lb)
P	$= [M]^t \{\Psi\}$
S_i	A vector of damping factors $S_i = 1.$ or $S_i = 0.1$
$\{S\}$	Direction vector
$X_i, \{X\}$	A vector of variable values
$\{X_o\}$	Solution vector, $\{X\} = \{X_o\}$ when ϕ is at its minimum
$XMAXI_i$	A vector specifying the upper numerical limit for x_i $XMINI_i < X_i < XMAXI_i$
$XMINI_i$	A vector specifying the lower numerical limit for X_i $XMINI_i < X_i < XMAXI_i$

$\Delta X_i, \{\Delta X\}$	Corrections or incrementations of variable values X_i
$W_x W_y W_z$	Orthogonal components of ball rotational speed about its own axis (radians/sec)
W_o	Ball orbital speed (radians/sec)
α_o	Ball-outer raceway contact angle
β	Ball speed vector pitch angle
γ'	D/d_m
λ	Step size used in the Fletcher Powell Method
$\bar{\Phi}$	A constant value of ϕ corresponding to the assumed or correct vector of X
$\psi_i \; \{\psi\}$	A set of nonlinear equations having the variables X_j
ϕ	The function defined by $\phi = \sum_{i=1}^{i=N} \psi_i^2$

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EXPANSION AND IMPROVEMENT OF SKF COMPUTER PROGRAM SHABERTH

1. - INTRODUCTION

The objective of this effort was to produce a design and analysis tool in the form of a computer program, for the study of ball and cylindrical rolling element bearing performance under conditions of elastohydrodynamic (EHD) lubrication.

The program developed was designed to treat the complete multibearing-shaft system. It has been given the name SHABERTH, an acronym for "Shaft-Bearing-System-Thermal Analysis".

SHABERTH evolved from an analysis which could treat highly loaded, moderate speed shaft bearing systems such as those found in helicopter power transmissions. It is now a design and analysis tool addressing simulation of moderately loaded but ultra high speed gas turbine main shaft systems anticipated in design of future aircraft. The latter are expected to operate with bearing speeds greater than 3 million DN. (DN is the product of the bearing bore diameter expressed in millimeters, and the shaft speed in revolutions per minute.) The difference between these two applications noted is the degree to which bearing internal friction forces affect bearing performance.

When bearing loads are high and speeds moderate the bearing rolling element-raceway contact traction forces are large. They have the potential to exceed contact inlet drag, as well as cage friction and normal forces by perhaps an order of magnitude. At ultra high speeds, under moderate loading, the relative significance of the contact friction forces decreases with respect to the other friction effects. Rolling element and cage speeds with calculations based on epicyclic or raceway control assumptions no longer reflect reasonable estimates. Thus, the dynamics of such elements must be calculated with due recognition included for friction and inertia forces which act.

The increase in sophistication required to incorporate these calculations in the description of rolling element and cage positions and speeds is substantial. Accurate mathematical models of the physical phenomena are required. Their complexity in turn requires state-of-the-art numerical mathematics for solving the resulting systems of highly nonlinear equations.

To an extent the mathematical friction models were developed under Air Force Contract No. F33615-72-C-1467 and Navy MIPR No. M62376-3-000007. A cage model was developed under NASA Contract No. NAS3-19739 and installed in SHABERTH. Thus, the major friction related phenomena had been modelled and could be used successfully to predict bearing friction forces and heat generation rates present in heavily loaded bearings in which cage and rolling element speeds could be estimated with conventional methods.

The present effort had to address and incorporate in SHABERTH refinements in modelling. Additionally, nonlinear equation solution techniques had to be improved to treat the amplified influence of friction forces which affect performance in moderately loaded high speed bearings. Two parallel approaches were taken.

1. The first was to investigate and improve the behavior of the mathematical models in SHABERTH. The equations which they create were to be as linear as possible, while remaining consistent with physical reality. While making these investigations methods were sought to improve the nonlinear equation solver, SOLV13, present in SHABERTH.

2. The second effort was directed at investigating several nonlinear equation solution techniques which had appeared in the literature and were believed might be improved to exceed the modified Newton Raphson-Falsi techniques of SOLV13.

Details of these two efforts shall be outlined in Sections 2 and 3.

Under this contract in addition to enhancing the ability of SHABERTH to produce results, its actual modelling capabilities were expanded to allow bearing ring and rolling element material properties to be input, individually. This capability will allow proper modelling and study of the performance of bearings having components of different materials, i.e., (silicon nitride). The program was also modified to permit the solution of:

1) a single cylindrical roller bearing subject to radial and moment loading

2) a single ball bearing subjected to axial loading.

2. - BEARING MODEL MODIFICATIONS AND SOLUTION SCHEME IMPROVEMENTS

Numerical solution for rolling element bearing quasi-dynamic equilibrium has always presented difficulty. A single general program in all probability will not be generated to solve every problem to any desired level of accuracy. However, strides have been made to obtain such an ideal bearing design and analysis tool. The advent of high speed digital computers has enabled continued progress and it is believed that progress will continue as long as the problem is pursued.

The computation difficulty resides in solving large sets of nonlinear equations and the lack of an all powerful method for that purpose. At the outset of this portion of the effort, it was believed that within the constraints of contract time and money the modified Regula-Falsi, Newton-Raphson iteration techniques of SOLV13 were the best available. However, recognizing the additional computation demands made by the advanced level of sophistication in this work it was decided to attempt an upgrade of SOLV13. The improvements needed could be obtained by recognition of the following ideas:

1) The solution to the equation set would be easier if the equations could be made

   a) more linear
   b) load variable-force relationships were more unique.

2) Achievement of a solution would be more probable and faster if the variable values were confined to predetermined known limits within which they must lie.

3) The solution would be faster if the change in variable values from one iteration to the next were allowed to be only within certain limits, specified uniquely for each variable value. Control on variable value incrementation is referred to as damping.

The manner in which these ideas have been pursued are presented below.

2.1 Mathematical Model Changes.

One of the approaches to decreasing the difficulty in solving nonlinear equations is to make those equations less nonlinear. This approach was taken in the revision of both the rolling element cage and cage ring load displacement models. The details of these model changes are presented in the Program Users Manual.

Another substantial change in the mathematical models was the change in the concentrated contact, asperity friction relationship. This calculation was changed from a coulomb model to a model in which the asperity friction coefficient is a function of both, contact sliding and rolling speeds. The coulomb model requires the contact friction force to be the product of a constant friction coefficient and the normal load. Thus, as long as the load is constant, the friction force can not change regardless of changes in rolling element speeds.

The Figure 1 demonstrates the difference in models

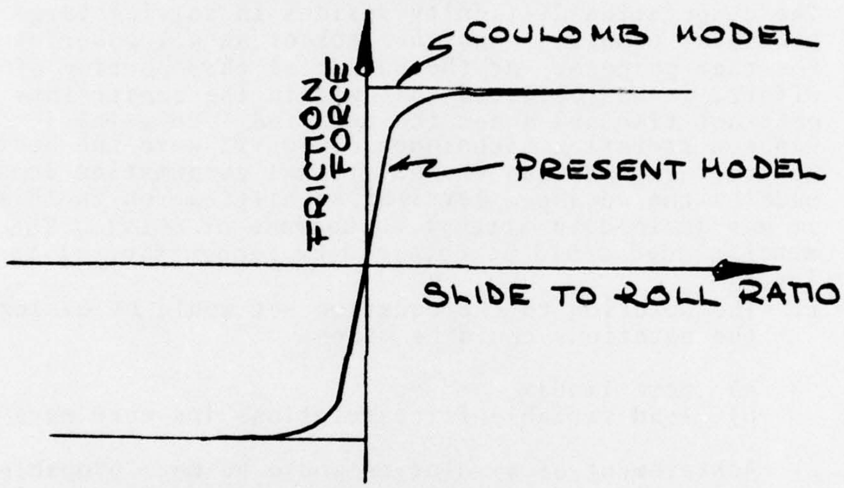

Fig. 1 Friction Force Versus Slide to Roll Ratio

Experience with SHABERTH has shown that asperity traction, more often than not, is responsible for larger forces than the traction resulting from lubricant shear.

2.2 Constraints on Variable Values

In the investigation of the solution of a generally loaded ball bearing test problem having thirty-three degrees of freedom (six for each of five elements and three for the cage), it was observed that for several sequential iterations, a few variables, associated with only one or two balls, were the most influential. Small changes in these values resulted in large changes in the equilibrium equation residues. As the influential variables converged, the less influential variables drifted to impossible values. Ultimately, the latter prevented convergence for the variable set.

The variables most prone to the above behavior were the y and z components of ball rotational speed in lightly loaded elements. Both of these components take on small values compared to the x component of speed. The proper sense of both components was of major importance in reaching a converged solution. Establishing this sense must be done prior to the start of the solution. It may be deduced from the direction of the outer and inner ring rotational speeds and the relative axial position of the inner ring with respect to the outer ring at the particular ball location.

The logic to perform the above function was introduced into the program and represents a refinement to the previous version of the code.

2.3 Solution Damping

The Regula-Falsi, Newton-Raphson scheme in SOLV13, solves a set of n nonlinear equations. The right hand sides of these equations, the residues, are systematically reduced and approach zero at solution. The procedure calculates corrections (ΔX_{iN}) to an existing set of variables (X_{iN}) according to Eq. 1.

$$X_{iN+1} = X_{iN} + \Delta X_{iN} \quad i=1,\ldots n \tag{1}$$

where: N indicates the current iteration
N+1 indicates the next iteration
n is the total number of unknowns

The solution is said to be converging from one iteration to the next if each set of corrections has the affect of reducing the equation residues.

In the solution scheme embodied in SOLV13, Eq. (1) is modified as follows:

$$X_{iN+1} = X_{iN} + f_{iN} \cdot \Delta X_{iN} \tag{2}$$

where: f_{iN} is a damping factor such that $0 < f_{iN} \leq 1$.

For each iteration, each variable has an independent damping factor. Four steps are used to set these factors.

1) The damping factors are initialized

$$f_{iN} = 1 \qquad i = 1,\ldots n \tag{3}$$

2) The value of X_{iN+1} is determined using Eq. (2), test and examined according to

$$XMINI_i > X_{iN+1} > XMAXI_i \tag{4}$$

If either test is true f_{iN} is halved, Eq. (2) is re-evaluated and the test is repeated. This process is permitted to occur 100 times for each variable. The objective of this scheme is to restrict the value which a variable is permitted, to that set defined by

$$XMINI_i \leq X_i \leq XMAXI_i \qquad (5)$$

After step 2 the individual f_i values may be different. $XMINI_i$ and $XMAXI_i$ are preset for both the thermal and bearing component equilibrium solutions.

3) The absolute value $|\Delta X_{iN}/X_{iN}|$ is calculated for i=1, n and the maximum value is retained and compared to the maximum value $|\Delta X_{iN-1}/X_{iN-1}|$. If the value at each damping factor is modified according to Eq. 6.

$$f_{i_{step3}} = f_{i_{step2}} \frac{|\Delta X_{iN-1}/X_{iN-1}|}{|\Delta X_{iN}/X_{iN}|} \quad i=1,\ldots n \qquad (6)$$

4) This step was taken from Wingo (8). At this point Eq. (2) is evaluated for all variables. The set of equations being solved is then evaluated with X_{iN+1}. The sum of squares of the equation residues is calculated and the test in Eq. (7) is performed.

$$\sum_{i=1}^{n} Eq^2_{iN+1} > \sum_{i=1}^{n} Eq^2_{iN} \qquad (7)$$

If the test in Eq. (7) is true f_i, i=1,...n is halved and step 4 is repeated. This procedure continues fifteen times or until the test fails.

If after fifteen halvings of f_i, the sum of squares of residues is not reduced, control is returned to the Newton Raphson scheme without any correction being applied to X_{iN}. The step size used to evaluate partial derivatives is altered and a new set of ΔX_{iN} is calculated. Steps 1) through 4) are repeated. As many as four attempts are made to recalculate ΔX_i in a single Newton-Raphson iteration point. If the test in Eq. (7) has not been passed, the scheme terminates. The variable values and equation residues are printed along with a warning stating "THIS IS THE BEST WE CAN

DO THE RESULTS MAY BE USEABLE". Whether or not the results are useable depends on the absolute value of the magnitudes of the residue values. Methods to assess useability are discussed in Ref. (1).

Another method of solution damping was tested in place of step 3) above and although it worked well in some instances, it actually hindered convergence in others. In this scheme $\Delta X_i/X_i$ was compared to S_i, a vector whose values were set to a constant value 0.1, or 1.0 depending upon the nature of X_i.

$$\Delta X_i/X_i > S_i \tag{8}$$

If for a particular variable, i=1, ...n the test in Eq. (8) was true , X_i for that variable was redefined such that

$$\Delta X_i = S_i \cdot X_i \tag{9}$$

This scheme thus damps the corrections to the variables individually. It was found that when two or more variables were closely coupled, convergence was prevented and the procedure was abandoned in favor of step 3) above.

3. METHODS FOR SOLVING SYSTEMS OF NONLINEAR EQUATIONS

The sets of equations generated by the description of bearing-shaft interactions in SHABERTH are highly nonlinear and complex. The increasing complexity in detailed representation of the physical problem has necessitated the exploration of alternate solution schemes.

For a set of N nonlinear equations with N variables, X_j,

$$\psi_i(X_j) = 0 \qquad i,j = 1,2,\ldots,N \tag{1}$$

the function

$$\phi = \sum_{i=1}^{N} \psi_i^2 \tag{2}$$

takes on the minimum value $\phi=0$ at all points satisfying Eq. (1). The function ϕ defined in Eq. (2) is convenient in that it has the same form as the least squares objective function in regression analysis methods for generating empirical formulas from experimental data. Therefore, some of the well developed solution techniques in regression analysis can be applied to solve Eq. (1). Additionally, there are several methods available for calculating the minimum of a function of many variables. These methods can also be used to solve Eq. (1) expressed in the form of Eq. (2).

Two methods have been adapted for solving Eq. (2), viz., the method by Fletcher and Powell [2] and that by Powell [3]. The former is a steepest descent procedure. It uses an iterative process to find the minimum of the function ϕ. The basic idea is to move from an initial point, X, along the vector with components [4]

$$-\frac{\partial\phi}{\partial X_1},\ -\frac{\partial\phi}{\partial X_2},\ \ldots\ldots,\ -\frac{\partial\phi}{\partial X_N}$$

whose values change continuously as the path is followed. The method described by Powell is a modified version of the Gauss Newton technique. It involves expanding Eq. (1) in N Taylor series and uses the results of linear least squares [4] in a succession of iterations.

In general, a steepest descent procedure is expected to converge for poor initial values but requires extensive computation time. The Gauss Newton technique, however, will converge rapidly for good starting estimates. In the ideal situation, use of the

first method should be made during the first several iterations. Then a switch to the second method should follow to achieve rapid convergence. The solution of a set of nonlinear equations, however, remains an art evolving into a science. In practical situations, the obtaining of a solution is more often than not related to the skill and past experience of the investigator rather than guaranteed by set procedure steps. A clear understanding of the function characteristics is always among the necessities for rapid convergence no matter what method or combination of methods is used. Therefore, some of the parameters in the techniques discussed have to be properly constrained. These constraints are dictated by the features of the function under consideration as well as the experience with the programs on the part of the investigator.

3.1 Fletcher and Powell Method -A

This method is based on a theory advanced by Davidson [5].

Express the function $\emptyset$ in the quadratic form

$$\emptyset = \bar{\emptyset} + \{A\}.\{X\} + \frac{1}{2}\{X\}.[H]\{X\} \tag{3}$$

where $\bar{\emptyset}$ is a constant value of $\emptyset$ corresponding to the assumed or current vector $\{X\}$, $\{A\}$ is a vector of constants, $\{X\}$ is a solution vector and $[H]$ is a matrix whose elements are the second order partial derivatives of $\emptyset$ with respect to the components of $\{X\}$.

The gradient vector $\{G\}$ can be obtained from Eq. (3) by differentiating $\emptyset$ with respect to the components of $\{X\}$, i.e.

$$\{G\} = \{A\} + [H]\{X\} \tag{4}$$

At a minimum value of $\emptyset$, $\{X\} = \{Xo\}$ and $\{G\} = 0$. Therefore,

$$\{A\} = -[H]\{Xo\} \tag{5}$$

or

$$\{G\} = -[H]\{Xo\} + [H]\{X\}$$

Multiplying both sides by $[H]^{-1}$, one obtains

$$\{Xo\} = \{X\} - [H]^{-1}\{G\} \tag{6}$$

In this method, the matrix $[H]^{-1}$ is not evaluated directly but approximated in the iteration process. The algorithm proceeds as follows:

(1) Select a starting point for the solution vector $\{X\}$.

(2) Compute a direction of search for the minimum,

$$\{S\}^{(k)} = - [F]^{(k)} \{G\}^{(k)} \tag{7}$$

where

$$[F] = [H]^{-1}$$

K is the iteration index and $\{S\}$ is the direction vector. It is seen from Eq. (6) that $\{S\} = \{Xo - X\}$. The matrix [F] can initially be represented by a diagonal matrix with the diagonal elements set equal to $|X_i/G_i|$ instead of the unit matrix suggested in [1]. When the absolute values of the $\{X\}$ components are of different orders of magnitude, the unit matrix can seriously impair convergence and in actual bearing problems lead to a convergence stall. This will be explained in the next step.

(3) A one-dimensional search is conducted in the direction chosen by the previous step for a minimum utilizing the relation,

$$\{X\}^{(k+1)} = \{X\}^{(k)} + \lambda \{S\}^{(k)} \tag{8}$$

derived from Eqs. (6) and (7). The factor λ is termed the step size. When close to the solution vector $\{Xo\}$, λ is unity as can be seen from Eqs. (6,7). The step size λ is calculated so that $\emptyset$ has a relative minimum at $\{X\}^{(k+1)}$. A simple algorithm for estimating λ can be found in [4]. Usually, the relative minimum will exist between $\{X\}^{(k)}$ and $\{X\}^{(k+1)}$ with λ in Eq. (8) expressed by

$$\lambda = \text{Minimum} \left(1, \frac{-2\emptyset}{\{G\}.\{S\}} \right)^{(k)} \tag{9}$$

However, when the time required for evaluating the function $\emptyset$ is considerable, it is advisable to use the value of λ calculated according to Eq. (9) as long as the function value of $\emptyset$ decreases. The algorithm for determining λ in [4] need only be used when $\emptyset$ diverges or becomes very small.

It is noted that when the absolute values of the components of $\{X\}$ differ by orders of magnitude, the same phenomenon will will exist in $\{G\}$ in a bearing problem. If a unit matrix is assumed for [F] in Eq. (7), then $\{S\} = -\{G\}$, and λ can be very small in Eq. (9) for a decreasing function $\emptyset$. Thus, the improvements in $\{X\}^{(k+1)}$ in Eq. (8) can be negligibly small. This explains the "convergence stall" mentioned in step (2).

(4) A convergence check based on a specified small value of $\emptyset$ is made. If convergence is achieved, the procedure is terminated; otherwise a new search direction is chosen per step (2) with [F] calculated as follows:

$$[F]^{(k+1)} = [F]^{(k)} + [A]^{(k)} + [B]^{(k)} \qquad (10)$$

where

$$[A]^{(k)} = \frac{\{\Delta X\}^{(k)} \; \{\Delta X\}^{(k)t}}{\{\Delta X\}^{(k)t} \; \{\Delta G\}^{(k)}}$$

$$[B]^{(k)} = \frac{[F]^{(k)} \; \{\Delta G\}^{(k)} \; \{\Delta G\}^{(k)t} \; [F]^{(k)}}{\{\Delta G\}^{(k)t} \; [F]^{(k)} \; \{\Delta G\}^{(k)}}$$

$$\{\Delta X\}^{(k)} = \{X\}^{(k+1)} - \{X\}^{(k)}$$

$$\{\Delta G\}^{(k)} = \{G\}^{(k+1)} - \{G\}^{(k)}$$

in which t represents the transpose of a vector, i.e. a column vector is transposed to a row vector. A new one dimensional search is then performed in the new direction. The process is repeated until convergence is obtained.

3.2 Powell Method _B

The basic purpose of this method was to modify the Gauss Newton technique to eliminate the necessity of derivative calculations. The derivatives are approximated by finite differences implicitly without requiring substantially more function evaluations. When the accuracy in calculating derivatives numerically is not dependable and the number of function evaluations is required to be minimal, this method seems to be very attractive.

Eqs. (1) are first linearized by expanding them in N Taylor series. Only linear terms are retained,

$$\psi_i = \bar{\psi}_i + \sum_{j=1}^{N} \frac{\partial \bar{\psi}_i}{\partial x_j} \Delta x_j \qquad (11)$$

where $\bar{\psi}_i = \psi_i(\bar{x}_j)$, $\Delta x_j = x_j - \bar{x}_j$ and $\bar{x}_j$ are the current values of the components of vector $\{\bar{x}\}$.

Substituting Eqs. (11) into Eq. (2) and then setting

$$\frac{\partial \emptyset}{\partial x_j} = 0 \qquad j = 1,2,\ldots,N \qquad (12)$$

one obtains the Gauss Newton formulation. In matrix notation, this can be written as

$$[M]^{(k)t} \; [M]^{(k)} \; \{\Delta X\}^{(k)} = - [M]^{(k)t} \; \{\psi\}^{(k)} \qquad (13)$$

where

$$\{\Delta X\}^{(k)} = \{X\}^{(k+1)} - \{X\}^{(k)}$$

[M] is the Jacobian matrix with elements $\partial\psi_i/\partial x_j$, t denotes the transpose of a matrix and K is the iteration index. Note if $[M](k)t$ are removed from both sides of Eq. (13), it reduces to the well known Newton Raphson formulation.

The algorithm of the method proceeds as follows:

(1) A starting point for the solution vector $\{X\}$ is selected and a direction vector $\{S\}$ with a component of unity in each coordinate direction is assumed.

(2) The Gauss Newton equations are set up and solved for $\{\Delta X\}^{(k)}$.

(3) The vector $\{\Delta X\}$ obtained in step (2) is used to calculate a new direction vector, which, in normalized form, can be written as

$$\{S\}^{(k+1)} = \frac{\{\Delta X\}^{(k)}}{|\Delta X|^{(k)}} \qquad (14)$$

(4) A one-dimensional search for a relative minimum is then conducted in the new direction using the same relationship represented by Eq. (8). The procedures described by Powell [6] are used to find the step size λ, which will yield a minimum function value of $\emptyset$ in one iteration.

(5) When the one-dimensional minimum has been found, an overall convergence test against the specified small value of $\emptyset$ is performed. The convergence criterion suggested in [3] is that when both $\{S\}$ and $\lambda\{S\}$ in Eq. (8) have acceptably small components, then iteration should stop. This criterion, however, does not always guarantee that the value of $\emptyset$ is reasonably small, which is necessary for convergence to be established. If the convergence criterion is satisfied, the procedure is

terminated. If not,one of the previous direction vectors is replaced by the new direction vector. The vector to be replaced is the one with index corresponding to the maximum of the following quantities,

$$\left| \{P\}^{(k)} \cdot \{\Delta X\}^{(k)} \right|$$

where

$$\{P\}^{(k)} = [M]^{(k)t} \{\psi\}^{(k)}$$

The values of the derivatives in the [M] matrix in the new direction can be found by finite differences using values from the completed one-dimensional search. Thus, the Guass-Newton equations are now updated with respect to the new direction and are solved again for $\{\Delta X\}$. The process is repeated until convergence is achieved.

It is noted that the case where all the aforementioned quantities may be zeroes is not considered in [3]. When it happens, the position of the minimum can only be poorly determined. The situation can usually be corrected by changing the parameter limiting the step size which is to be supplied to the computer program [7].

3.3 Numerical Example

The methods discussed have been put in a subroutine subprogram named BOMBER, which has been inserted in an experimental version of SHABERTH. Test runs have been made on a ball bearing problem. The bearing geometrical dimensions are as follows:

(a)	Pitch diameter	190 mm
(b)	Diametral clearance	0 mm
(c)	Ball diameter	23.0187 mm
(d)	Contact angle	20 deg.
(e)	Inner and outer raceway curvatures	0.51/0.52

The bearing operating conditions are:

(a)	Thrust load	35580 Newtons
(b)	Inner ring speed	13460 RPM

The output contains the following seven unknowns:

(a) Ball displacement in the bearing axial direction.
(b) Ball displacement in the bearing radial direction.
(c) Ball velocity component in the bearing axial direction.
(d) Ball velocity component in the bearing radial direction.
(e) Ball velocity component in the bearing tangential direction.
(f) Ball orbital velocity.
(g) Relative displacement between ball center and cage pocket center.

For solving the set of seven nonlinear equations, the methods discussed performed very poorly. Fletcher-and-Powell's method reduced the value of ϕ from 1185.8 to 30.4 in 7 iterations. After that, the convergence became very slow. The computation was then switched to Powell's method, which further reduced ϕ to 18.7 in 18 iterations, and then experienced a convergence stall. The problem solver subroutine SOLV13 already in SHABERTH performed on the same problem with excellent results. It reduced the value of ϕ from 1185.8 to 2.4868×10^{-4} in merely 3 iterations.

At a first glance, the above comparisons clearly indicate that SOLV13 is superior to the other two methods explored. But this is a misleading generalization from particulars. SOLV13 has been tested extensively on bearing problems and in the process has evolved with the proper constraints for rapid convergence. The other two methods have not undergone the same refinements. If the three methods are applied to a different problem, one may expect different results. It was then decided to solve the following problem with a set of four highly nonlinear equations.

$$\psi_1 = (X_1 - X_3)^2 + (X_2 - X_4)^2 + (X_1 + X_2 + X_3 + X_4)^2 - 16 = 0$$

$$\psi_2 = X_1 \sin\left(\frac{\pi}{2} X_3\right) + X_2 \cos\left(\frac{\pi}{2} X_4\right) - 1 = 0$$

$$\psi_3 = X_1 + X_2^2 + X_3^3 + X_4^4 - 4 = 0$$

$$\psi_4 = X_1 + 2X_2 + 3X_3 + 4X_4 - 10 = 0$$

A known solution for this set is

$$X_1 = X_2 = X_3 = X_4 = 1$$

Assuming starting values of X_i to be

$$X_1 = X_2 = X_3 = X_4 = 3$$

the results obtained are as follows:

3.3.1 Fletcher and Powell Method

In this method the initial diagonal matrix for [F] (see Eq. (7)) are assumed in two different ways. In case (a), the diagonal elements were set equal to

$$|X_i / G_i|$$

in the first four iterations. Succeeding values for (F) were calculated using Eq. (10). Results are tabulated as shown below:

Case (a)

No. of Iteration	Value of $\emptyset$
1	3.0256×10^{4}
2	2.4817×10^{4}
3	1.6101×10^{2}
4	2.0413
5	1.5235×10^{-2}
6	1.8825×10^{-5}
7	3.1739×10^{-7}

In Case (b), the same assumption for the diagonal matrix was used only in the first iteration and a unit matrix used in the next three iterations before going to Eq. (10) for values of [F]. Results obtained are as follows:

Case (b)

No. of Iteration	Value of $\emptyset$	No. of Iteration	Value of $\emptyset$
1	3.0256×10^{4}	14	2.3459×10^{-3}
2	2.4817×10^{4}	15	1.7255×10^{-3}
3	2.0023×10^{2}	16	1.1738×10^{-3}
4	3.5718	17	7.8990×10^{-4}
5	1.4617	18	6.3554×10^{-4}
6	2.6223×10^{-1}	19	5.6346×10^{-4}
7	8.9737×10^{-2}	20	3.6855×10^{-4}
8	2.4277×10^{-2}	21	2.5433×10^{-4}
9	1.3055×10^{-2}	22	7.3626×10^{-5}
10	8.5633×10^{-3}	23	2.4264×10^{-5}
11	6.0581×10^{-3}	24	1.5651×10^{-5}
12	4.5206×10^{-3}	25	1.2606×10^{-5}
13	3.1359×10^{-3}	26	8.7025×10^{-6}

It is seen that the effect of the assumed values for [F] in the first N iterations has great influence on the speed of convergence. It is believed that for each specific function, there is an optimum choice for [F]. From Eqs. (7) and (8), an optimum choice of λ should also speed up convergence.

3.3.2 Powell Method

In this method, the input data include a vector $\{E\}$ which specifies the absolute accuracy limits on the change of the solution vector $\{X\}$ between iterations and a parameter ESCALE for limiting the step size. Different values were assumed for $\{E\}$ and ESCALE. In case (a), $\{E\} = 10^{-4}\ \{X\}$ and ESCALE = 10^3. Results are tabulated as follows:

Case (a)

No. of Iteration	Value of ϕ	No. of Iteration	Value of ϕ
1	3.0256×10^{4}	14	1.2850×10^{-2}
2	2.6408×10^{4}	15	1.2308×10^{-2}
3	1.6054×10^{4}	16	1.2169×10^{-2}
4	4.9133×10^{3}	17	1.0051×10^{-2}
5	1.2008×10^{2}	18	7.6573×10^{-3}
6	5.4462×10	19	6.1980×10^{-3}
7	4.0010	20	4.6055×10^{-3}
8	5.4152×10^{-1}	21	4.4769×10^{-3}
9	3.4274×10^{-2}	22	2.3138×10^{-3}
10	3.3390×10^{-2}	23	1.6479×10^{-4}
11	3.2167×10^{-2}	24	3.2553×10^{-5}
12	1.4647×10^{-2}	25	5.1502×10^{-6}
13	1.2851×10^{-2}	26	2.9703×10^{-7}

Total no. of function evaluations = 132.

In Case (b), $\{E\} = 10^{-3}\{X\}$ and ESCALE = 10^3. The following results were obtained:

Case (b)

No. of Iteration	Value of $\emptyset$	No. of Iteration	Value of $\emptyset$
1	3.0256×10^4	12	1.1717×10^{-1}
2	2.5688×10^4	13	1.1184×10^{-1}
3	2.4588×10^4	14	4.7794×10^{-2}
4	2.4550×10^4	15	8.2560×10^{-3}
5	1.9918×10^4	16	5.1906×10^{-4}
6	1.0901×10^4	17	1.8922×10^{-5}
7	1.2136×10^3	18	2.0257×10^{-6}
8	4.9442×10^1	19	1.4810×10^{-6}
9	2.8403×10^1	20	1.7413×10^{-7}
10	3.1453	21	6.3507×10^{-8}
11	9.3839×10^{-1}	22	1.0573×10^{-8}

Total no. of function evaluations = 93.

In case (c), $\{E\} = 10^{-3}\{X\}$ and ESCALE = 5×10^3. The results obtained are shown below:

Case (c)

No. of Iteration	Value of ϕ	No. of Iteration	Value of ϕ
1	3.0256×10^4	14	1.1683
2	2.5598×10^4	15	1.1073
3	1.1546×10^4	16	1.1073
4	1.9929×10^3	17	1.1073
5	7.7313×10^2	18	9.2596×10^{-1}
6	7.2866×10^2	19	9.2596×10^{-1}
7	5.7259×10^2	20	9.2596×10^{-1}
8	3.4214×10^2	21	9.2596×10^{-1}
9	3.4114×10^2	22	9.1645×10^{-1}
10	3.0366×10^2	23	8.1042×10^{-1}
11	2.0606×10	24	8.1042×10^{-1}
12	3.6928	25	8.1042×10^{-1}
13	1.2196	26	7.5514×10^{-1}

Total no. of function evaluations = 151.

It is seen that the best results were obtained in Case (b). Increasing the value of ESCALE in Case (c) resulted in failure to converge. These results clearly indicate that there are optimum choices for these parameters for any specific function to achieve rapid convergence.

3.3.3 SOLV13

The solution technique, which is based on a combination of the Regula-Falsi and Newton-Raphson methods, was used to solve the same problem. The results calculated follow:

No. of Iteration	Value of Ø	No. of Iteration	Value of Ø
1	3.0256×10^4	14	8.6801×10
2	2.9099×10^4	15	5.5226×10
3	1.8725×10^4	16	2.9799×10
4	1.3936×10^4	17	6.8156
5	1.1845×10^4	18	4.8235
6	7.0244×10^3	19	2.2842×10^{-2}
7	4.0705×10^3	20	2.9017×10^{-3}
8	2.3038×10^3	21	6.2933×10^{-4}
9	1.2547×10^3	22	1.1100×10^{-4}
10	6.6686×10^2	23	2.0917×10^{-5}
11	3.2925×10^2	24	3.7563×10^{-6}
12	2.1160×10^2	25	5.7764×10^{-7}
13	1.4750×10^2		

From the results of the second problem, the methods investigated seem to have a definite advantage over SOLV13, e.g. Fletcher and Powell. It is, therefore,logical to expect that if proper constraints are introduced into these methods, they can be made into very effective tools for solving realistic bearing problems. The proper optimization of constraints, however, can only be obtained through experimentation with the highly nonlinear equation sets characteristic of bearing analysis.

As the detail and understanding increase in computerized simulation of bearing performance current equation solvers are taxed to the limits of their capabilities. It is believed that additional experimentation with the methods described will yield the more powerful tools needed to meet the pressing mathematical needs of state of the art design and analysis. However, current results from both test problems highlight the development needed for the alternate schemes evaluated, SOLV13 is therefore the best method available. It is thus the only one in SHABERTH at this time.

4. - DISCUSSION OF SAMPLE PROBLEMS

4.1 Introduction

Solutions to two sample problems were chosen to demonstrate the use of SHABERTH. The objective of the sample problem executions was to demonstrate the prime and secondary (optional) capabilities of SHABERTH. The prime capability, to calculate shaft-bearing system performance parameters under specified conditions of load, speed and temperature, is demonstrated by the analysis of the high speed rolling element bearing test rig operated by the Aero Propulsion Laboratory, Lubrication Branch, at the Wright-Patterson Air Force Base. The study of the rig performance also demonstrates the optional calculation of bearing operating clearances as affected by system radial thermal gradients, ring rotational speeds, rolling element-raceway loading and cold shaft and housing fits.

The second sample problem which calculates the steady state thermal performance characteristics of the CH-53 helicopter transmission power input shaft, demonstrates the SHABERTH option to calculate system steady state temperatures as a function of bearing frictional heat generation. SHABERTH can also calculate transient thermal performance characteristics and has been used in this manner to predict time to failure of a system, subsequent to the loss of lubrication, Ref. (9).

In addition to demonstrating the optional consideration of physical phenomena which affect shaft bearing system performance, the high speed test rig problem has been used to generate results utilizing NPASS=1,2 and 3 solution levels of SHABERTH. These levels consider with increasing complexity, the impact of friction forces upon system performance. Computer solution time is included in the summary of results to demonstrate the economics of each solution level.

4.2 Discussion of the Analysis of the Wright-Patterson Aero Propulsion Laboratory Lubrication Branch High Speed Rolling Element Bearing Test Rig

Figure 2 is a cross section of the modelled test rig. The 209 size cylindrical roller bearing labeled L and the 6220 size split inner ring ball bearing labeled A are the shaft support bearings in the assembly. A is the test bearing and is shown in detail in Fig. 3. All input data to SHABERTH, required to describe bearing A were taken from Fig. 3 with the exception of the ball and raceway asperity slope angles which were assumed to be two degrees. The input data used to describe bearing L reflects the standard SKF Industries NU 209 configuration.

The lubricant type (MIL-L-7808G), shaft and housing fits, system temperatures (used to evaluate bearing operating clearances, lubricant viscosity and pressure viscosity coefficient at outer and inner raceway-ball contacts and for the bulk lubricant) were supplied by the Lubrication Branch of the Aero Propulsion Laboratory. The estimates for the percent lubricant in the bearing cavities, the film replenishment layer thicknesses and the asperity friction coefficients were made by SKF personnel and are consistent with the recommendations made in the SHABERTH User's Manual, Ref. (1).

The rig in Figure 2 appears to be a three bearing support system. However, the center bearing, denoted G, is loaded axially and radially through its housing and is the means by which the shaft is loaded. Thus, for SHABERTH input, bearing G is replaced with the radial and axial shaft loading, plus a point moment estimated to arise from the combined radial and axial loading on G. The radial and axial load plus the shaft speed were provided by the Lubrication Branch.

The relatively complex shaft geometry is well within the capabilities of the flexible shaft analysis in SHABERTH. Shaft internal and external diameters at points of change are input and are used to establish the shaft flexural characteristics.

SHABERTH output from solution level, NPASS=2 is presented in Appendix I. The output should be self explanatory. However, the SHABERTH User's Manual provides additional detail on output input definitions.

SHABERTH was executed with similar input at both,levels 1 and 3. A comparison of results and computer solution time, provide useful insights into the use of SHABERTH and into system performance predictions.

Solution level 1, solves the shaft-bearing equilibrium equations considering rolling element raceway elastic contact forces and rolling element centrifugal forces. Ball orbital and rotational speeds are estimated using methods which approach outer raceway control theory described below.

The ball speed vector pitch angle β is calculated according to Eq. (7.50), Ref. 10 .

$$\tan\beta = \frac{\sin\alpha_o}{\cos\alpha_o + \gamma'} \tag{15}$$

where: α_o is the ball-outer raceway contact angle

$\gamma' = D/dm$

D is the ball diameter

dm is the bearing pitch diameter.

β corresponds to $(\pi - \tan^{-1}(Wy/Wx))$ where $\tan^{-1}(Wy/Wx)$ is printed in SHABERTH output.

Given β from Eq. (15), the Wx and Wy components of ball rotational speed as well as the ball orbital speed W_o are calculated assuming no relative ball-raceway slip in the tangential direction at the center of either outer or inner raceway contacts.

The yaw component of ball rotational speed Wz, is estimated to be

$$Wz = -1. \times 10^{-5}\ Wy \cdot W_o \qquad (16)$$

where W_o is the ball orbital speed.

Roller orbital and rotational speeds are estimated using epicyclic conditions. Upon satisfying this shaft-bearing equilibrium condition rolling element orbital and rotational speeds are recalculated, taking into account ring displacements and ball contact angle variations. A single pass is then made through the friction and lubrication subroutines wherein elastohydrodynamic (EHD) film thickness, friction forces and frictional heat generation rates are calculated. No attempt is made to arrive at that set of rolling element positions and speeds which will place each element and the cage in force and moment equilibrium.

Solution level NPASS=2 proceeds as does level 1, through the elastic, system solution. The relative outer-inner ring position thus obtained is held fixed. The equilibrium positions and rotational and orbital speeds for all rolling elements and the cage are determined for all bearings, one bearing at a time. The equilibrium state requires all rolling elements and the cage, to be in force and moment equilibrium considering all rolling element-raceway and rolling element-cage normal and friction forces. Inertia forces including centrifugal force and the two gyroscopic moments acting on each element, are also included. The interaction between the cage and ring on which it is piloted is considered. Note that, with

the friction forces included, the shaft applied loading is no longer equilibrated by the bearing reaction forces.

The NPASS=3 solution proceeds until all rolling element and cage equilibria are satisfied. Bearing inner ring reaction forces are required to equilibrate the shaft applied loading. At this level, the rolling element raceway reaction forces which balance the applied loading, are comprised of friction as well as normal forces.

Although the input data for the three solutions were similar they were not identical. In both, the level 1 and 2 solutions, the analysis which calculates bearing operating diametral clearance,based upon cold shaft and housing fits, thermal gradients, ring centrifugal expansion and ring loading, was employed. To reduce calculation time in the level 3 solution, this external, iterative calculation was eliminated. It was intended to specify the operating clearance predicted by the lower level solutions (in both cases, -0.0228 mm for the ball bearing) at input. The negative number indicates a reduction in clearance. Inadvertantly -0.00228 mm was actually input. The only substantial impact this had on results was to increase the shaft axial displacement required to equilibrate shaft loading. Table 1 shows the comparison of ball bearing results from the three solution levels. The roller bearing operated very close to epicyclic conditions at all solution levels and therefore, that data is not tabulated.

A fourth set of results is presented from a second NPASS=1 solution with the estimates of the ball speed vector pitch angle (as calculated by Eq. (15)) reduced by a factor of 10. Also Eq. (17), rather than (16) was used to estimate the Wz component of rotational speed

$$Wz = -0.75\ Wy \frac{W_y \cdot W_o}{|W_y \cdot W_o|} \qquad (17)$$

The reasons for obtaining this second NPASS=1 solution are discussed later.

Before the results of Table 1 are discussed, it is important to note that the test bearing under study was subjected to heavy loads. Additionally, there was not an excessive amount of lubricant in either bearing nor was there any other factor which would tend to induce cage slip. Consequentially, the estimates of rolling element orbital speeds used in the level 1 solutions are accurate to within 4% of the level 3 solution. As a consequence of the low pitch angles, and the absence of gross sliding in the ball raceway contacts, ball orbital speed is slightly higher than would be predicted by raceway control. This effect accounts for the 4% deviation between level 1 and 3 orbital speed predictions noted above. Should significant cage slip be predicted in the level 2 solution, level 1 results would differ substantially from level 2, and level 3 would differ from level 2 results.

Table 1 points out that for the test rig assembly, the level 1 solution provides good estimates of the performance of the system at approximately 14% of the cost of the level 2 solution and at approximately 1.4% of the level 3 solution cost.

The results of the solution level 3 execution represent the accurate solution to the problem. The lower level solutions are approximations. For estimates of bearing deflections, fatigue life and EHD film characteristics, all solution levels produce similar results. The level 1 solution using raceway control type estimates of ball speeds is at variance with the remaining runs in the estimate of raceway heat generation rates, and of course the estimate of component speeds themselves.

The purpose of the solution denoted 1* was to demonstrate that the heat rate and component speed estimates at level 1 can be brought into line with the level 2 and 3 solutions in a very simple manner. Only two program statements require change. These changes in fact were not made to fit the data but simply reflect the estimates of component speeds which SHABERTH uses to begin the level 2 and level 3 solutions.

The component speed data from levels 2 and 3 indicates that the ball speed vector becomes substantially more parallel with the bearing axis than would be predicted by raceway control theory.

The low pitch angle tendency has been observed often, in many different ball bearing solutions from SHABERTH. It is postulated that insufficient traction forces develop in the ball race contacts to resist the gyroscopic moment generated by ball rotation about an axis orthogonal to the axis of ball orbit.

$$Mgz = -JW_0Wy \tag{18}$$

Typically, ball equilibrium is satisfied with relatively small values of Wy. This observation has been used to speed solutions by using only one tenth of the pitch angle calculated with Eq. (16) as the initial estimate.

The speed vector pitch angle predicted by SHABERTH will increase with increasing traction coefficients. This has been observed using a version of SHABERTH containing an EHD film thickness model developed by Lowenthal et al, Ref. (11) and a traction model developed by Allen, Ref. (12). The combination of these models produce higher traction coefficients, than do the SKF models in SHABERTH. The identical problem solved with SHABERTH defined herein and the alternate version, produced speed vector pitch angles of practically zero and greater than would be predicted by outer raceway control, respectively.

As a matter of interest, the generality of the SKF traction model within SHABERTH provides a very simple means to increase the traction coefficient by simply increasing the asperity traction coefficient specified at input. To date, experience has been limited to use of a value of 0.1 which is consistent with values found in the literature. However, Cheng (13) recently has suggested that values up to approximately 0.5 may be valid.

The prime purpose behind the sample problem executions was to demonstrate a level of performance capability. The successful execution of the three levels of solution has also shown how SHABERTH should be used most economically in the solution of a multi-bearing system. Namely, if a level 2 solution indicates less than 5% cage slip, the level 1 solutions will produce good estimates of bearing deflections, fatigue life, and EHD film thickness. The level 2 solution should be used to make an accurate assessment of bearing heat generation rates. The level 3 solution should be used only when cage slip is shown to be significant from a level 2 solution. When level 3 is used every effort should be made to simplify the problem. Temperature maps and the change in clearance analysis should not be executed in order to save computing costs.

4.3 Discussion of CH-53 Steady State Modelling Results

The output from the CH-53 test problem is contained in Appendix 2. The system contains one 216 size cylindrical roller and a stack of four 6216 size split inner ring ball bearings. The bearing heat rates were calculated executing SHABERTH at the NPASS=1 level. With two clearance change iterations permitted for each thermal iteration, the bearings act as heat sources which supply heat to the temperature nodes representing inner and outer rings, rolling elements and lubricant. Additional heat sources include a gear mesh and a seal which are specified by constant heat rate values at input.

All initial system temperatures were set at an estimated value of 75°C. Bearing performance is then determined based upon these temperatures, the bearing heat rates serve as input to the temperature calculation scheme which in turn produces a new set of system temperatures. These new temperatures affect bearing clearance and most notably lubricant viscosity in the next calculation of shaft bearing system performance parameters. Six iterations, calculations of bearing system performance, are required before the equilibrium condition is achieved. Equilibrium

is satisfied when a check of all system temperatures, comparing two sequential iterations reflect less than a 1°C change.

The CH-53 nodal map and the equilibrium temperatures are presented in Fig.   The numbers which appear following a slash, e.g. /106 for node (7) indicate actual measured temperatures obtained from Ref. (14).

Although it is not included in Appendix 2, shaft-bearing system output data may optionally be printed after each calculation of bearing frictional heat rates. This data allows the user to observe system performance as a function of temperature. The option also serves as a precaution against obtaining no output data should the run fail in a late stage of execution.

Since the program input is printed, the thermal data input serves as a good example, to be reviewed along with the *SHABERTH* User's Manual, when preparing thermal data for another system.

5. - CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In 1972 an effort was begun by SKF Industries, Inc. under the sponsorship of the Air Force and Navy to develop an analytical tool for the analysis of ball bearings in gas turbine engines. The prime objective of this effort was to include as much of the knowledge on EHD lubrication as possible, in a fashion easily useable by a bearing system designer.

With the completion of this work in the form of SKF Computer Program SHABERTH,not only the ball bearing but the cylindrical roller bearing can be analyzed with state-of-the-art lubrication and friction models. Additionally, the complete shaft bearing system can be treated with the complex interaction of shaft and bearing displacements properly taken into account.

The effects of bearing friction with full or partial EHD films on rolling element and cage dynamics is treated. The effects of EHD film thickness and bearing surface topography on bearing fatigue life have been modelled and applied to both ball and cylindrical roller bearings. The bearing cage is modelled in a comprehensive manner. Rolling element-cage loading is determined as a function of rolling element-raceway and cage-ring friction forces. The properties of the shaft, bearing and housing materials may be input thus permitting the study of non steel components.

5.2 Recommendations

Evaluation of the physical phenomena considered in SHABERTH require the solutions for large systems of nonlinear equations. As noted in this report, a reliable generally applicable, technique for this purpose does not exist. The pursuit of such a tool should be encouraged at every opportunity.

SHABERTH in its current form offers a unique vehicle for extending the capabilities of bearing system design. The following opportunities for a cost-effective return on additional design and analysis tool development are:

1) The inclusion of tapered and spherical roller bearing modules.

   Need: Helicopter transmissions and geared turbo fan engines.

2) Expansion to a multishaft system with shaft interactions.

   Need: To compute inner shaft bearing performance.

3) A model for lubricant distribution within a bearing which would treat lubricant delivery methods (jet or through race) and address the cage as an active rather than passive element.

   Need: Ultra high speed bearing operation where lubricant delivery efficiency is a paramount factor in obtaining the required operating speed.

4) Based on the premise that bearing instabilities, such as those which occur in sparsley lubricated gyro bearings, result from changes in the frictional characteristics within the bearing, SHABERTH should be used to evaluate changes in bearing internal forces which lead to instabilities.

   Need: Gyro bearing instability persists as a problem with minimal understanding of cause and effect relationships.

5) Add a flexible ring analysis to the cylindrical roller module.

   Need: To correctly model the influence of out of round bearing preload when this approach is used to reduce cage slip.

6) The analysis should be expanded to permit a flexible housing represented by discrete spring constants at each bearing location.

   Need: To accurately obtain solutions in those cages where the housing stiffness is comparable to or less than that of the shaft.

7) Create rotor - bearing stability analysis module.

Need:The nonlinear displacement load response of bearings is poorly represented in current stability analysis programs. The detail present in SHABERTH would create powerful insight in the general stability and design of rotor bearing systems in engine, transmission and machine tool applications.

8) Parametric analysis - program exercise.

Need:The utility and optimum return on sponsor investment in as complex a program as SHABERTH is to be found by two procedures:

a) Specific problem simulation - e.g. steady state or time transient thermal analysis of WPAFB high speed bearing test rig

b) Generation of an enhanced manual (curves and guidelines) - to demonstrate the effects of various input parameters upon system performance. This will reduce the amount of program usage experimentation which each user will now have to undertake.

The "pump-priming" activity of b) will effect wider recognition for SHABERTH as an essential tool in the state-of-the-art bearing system creation and evaluation.

As SHABERTH is used throughout the industry, additional ideas for enhancement should come forth.

SHABERTH represents a state-of-the-art tool for the analysis of ball and cylindrical roller bearing shaft systems. Its use should be encouraged within the industry to upgrade bearing system design and to provide a degree of commonality in bearing calculations among mechanical system suppliers.

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TABLE 1

TEST BALL BEARING PERFORMANCE PARAMETERS PREDICTED BY SHABERTH AT VARIOUS SOLUTION LEVELS FROM THE ANALYSIS OF THE AERO PROPULSION LABORATORY ROLLING ELEMENT BEARING TEST RIG, SHAFT SPEED 15000 RPM, APPLIED SHAFT LOADING AXIAL X 8896 N, RADIAL Y 2224 N, MOMENT Z 4000 N-mm

Solution Level		Bearing Linear (mm) and Angular (radians) Displacements					Bearing Reaction Forces (N) and Moments (N-mm)				
		Axial	Radial Y	Radial Z	Angular Y	Angular Z	Axial (N)	Radial Y (N)	Radial Z(N)	Moment Y	Moment Z
NPASS	1	0.0068	-0.0075	--	--	-3.43×10^{-4}	8896	1482	-5	-3	-72920.0
	1*	0.0056	-0.0073	--	--	-3.41×10^{-4}	8896	1483	-4	-3	-73720.0
	2	0.0056	-0.0073	--	--	-3.41×10^{-4}	9074	1477	-	657.	-73230.0
	3	0.0219	-0.0081	--	--	-3.66×10^{-4}	8896	1491	--	133.	-76780.0

	Bearing Fatigue Life (hours), Life Improvement Factors, Film Thickness h_i (micrometers), Film Thickness/Surface Roughness Ratio, h/σ							
	L_{10} Outer	L_{10} Inner	L_{10} Bearing	Material-Lube Life Factor Outer	Material-Lube Life Factor Inner	h_{Outer}	h_{Inner}	h/σ_o	h/σ_i
1	2786	2288	1346	2.68	2.55	0.115	0.106	1.50	1.39
1*	2583	2294	1302	2.72	2.53	0.117	0.104	1.53	1.37
2	2519	2223	1265	2.71	2.53	0.117	0.105	1.52	1.37
3	2654	2505	1381	2.72	2.52	0.117	0.104	1.53	1.37

	Bearing Heat Generation Rates (watts)					
	Outer	Inner	Drag	Ball-Cage	Cage-Land	Total
1	210.0	324.0	720.0	18.3	25.1	1297.0
1*	838.0	710.0	787.0	22.1	23.7	2382.0
2	601.0	607.0	782.0	22.8	23.8	2037.0
3	593.0	595.0	796.0	22.6	23.5	2030.0

		Ball Speeds (rad/sec), Contact Load (N), Hertz Stress (N/mm^2) and Contact Angles (Deg.) at the Maximum Loaded Ball								
		W_x	W_y	W_z	W_o	Q_o	Q_i	H_z	H_{z_i}	α_o	α_i
NPASS	1	-5653.	1530.	-11.	704.8	2084.	1185.	1547	1651.	17.18	31.31
	1*	-6294.	162.	-121.	731.4	2148.	1181.	1563.	1649.	16.69	31.47
	2	-6279.	182.	-39.	728.6	2155.	1189.	1564.	1652.	16.64	31.49
	3	-6330.	171.	-38.	733.6	2148.	1175.	1563.	1646.	17.04	32.62

		Computer Time Required for Solution	
		CDC 6600	UNIVAC 1108
NPASS	1	16 seconds	22 seconds
	1*		20 seconds
	2	112 seconds	
	3	1157 seconds	

1* - Solution Level 1 with revised estimates of ball component speeds.

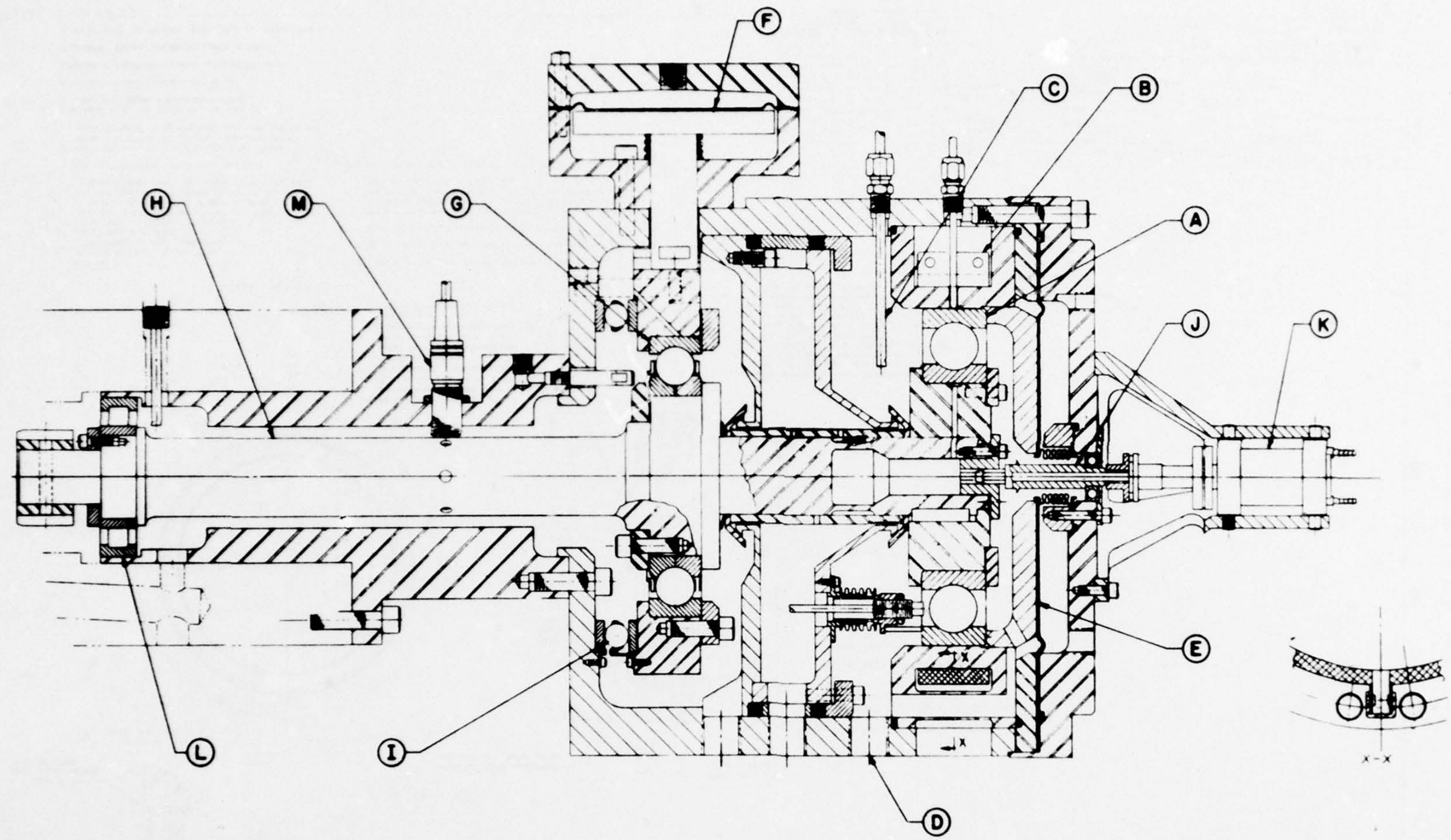


Figure 2. Cross Section of Rolling Element Bearing Test Machine

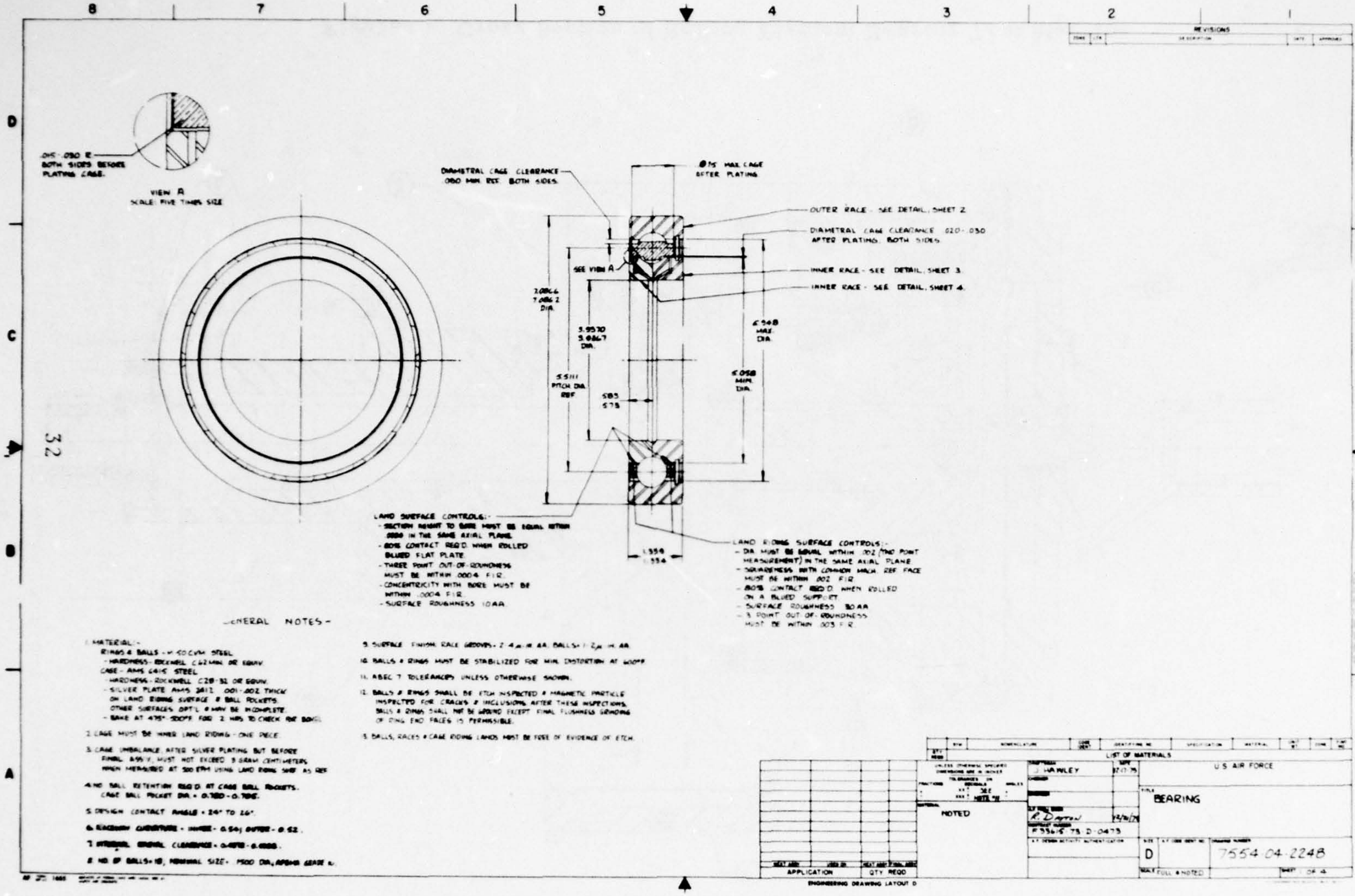
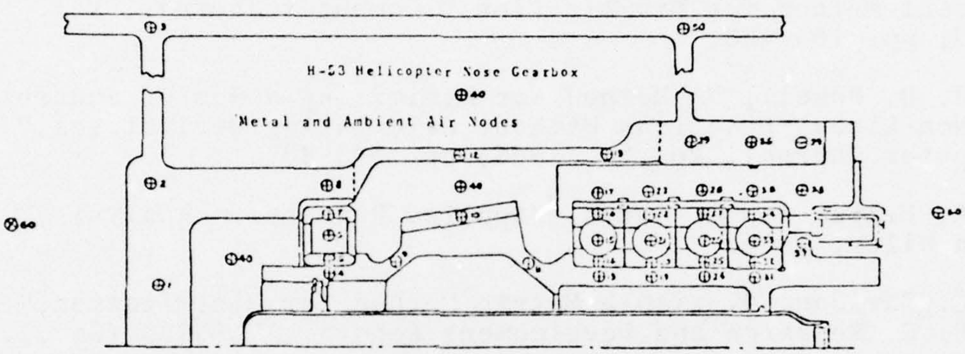


FIGURE 3. 6220 SIZE SPLIT INNER RING TEST BEARING

Fig. 4. CH-53 Power Input Module Nodal Maps and Steady State Temperatures

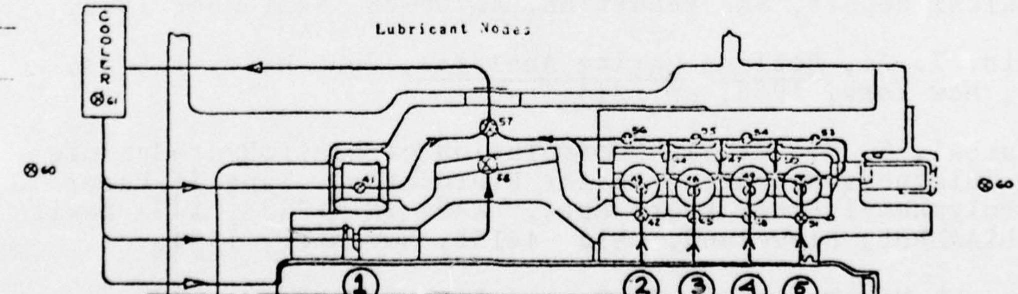


CALCULATED TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
1	93.103	2	94.718	3	80.748	4	115.434	5	117.314/122
6	113.634	7	106.140/106	8	102.353	9	107.245/89	10	[illegible]
11	95.107/65	12	101.027	13	78.735	14	82.319	15	[illegible]
16	84.951/92	17	86.153	18	88.457	19	79.555	20	[illegible]/96
21	94.332	22	88.084/93	23	87.388	24	80.050	25	[illegible]/62
26	94.609	27	88.393/90	28	87.313	29	86.435	30	[illegible]
31	81.989	32	87.267	33	95.328	34	88.343/87	35	[illegible]
36	85.144	37	103.561	38	84.396	39	83.695	40	92.442
41	101.703	42	72.266	43	78.785	44	90.902	45	72.434
46	84.750	47	94.703	48	72.632	49	85.078	50	[illegible]
51	73.183	52	86.022	53	95.677	54	95.415	55	95.130
56	93.922	57	101.778	58	87.757				

KNOWN BOUNDARY TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
59	75.000	60	24.000	61	70.000				



/XXX Indicates Experimentally Measured Temperatures

○ Designates Bearing Numbering Scheme

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APPENDIX I

WPAFB LUBRICATION BRANCH ROLLING ELEMENT

BEARING TEST MACHINE ASSEMBLY I

SHABERTH OUTPUT

```
*** S H A B E R T H / S K F  **  TECHNOLOGY DIVISION  S K F  INDUSTRIES INC.  ** S H A B E R T H / S K F ***
WPAFB LUBRICATION BRANCH * R.E.B. TEST MACHINE ASSEMBLY I * SOLUTION LEVEL 2

     THIS DATA SET CONTAINS  2  BEARINGS
      BEARING NO. (1) -   CYLINDRICAL ROLLER BEARING
      BEARING NO. (2) -   BALL BEARING

     THE MAXIMUM NUMBER OF FIT ITERATIONS ALLOWED IS  2 AND THE RELATIVE ACCURACY REQUIRED IS  .00010
```

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UNLESS OTHERWISE STATED, LINEAR DIMENSIONS ARE SPECIFIED IN MILLIMETERS, TEMPERATURES IN DEGREES CENTIGRADE, FORCES IN NEWTONS, WEIGHTS IN KILOGRAMS, PRESSURES AND ELASTIC MODULI IN NEWTONS PER SQUARE MILLIMETER, ANGLES AND SLOPES IN DEGREES, SURFACE ROUGHNESS IN MICRONS, SPEEDS IN REVOLUTIONS PER MINUTE, DENSITY IN GRAMS PER CUBIC CENTIMETER, KINEMATIC VISCOSITY IN CENTISTOKES AND THERMAL CONDUCTIVITY IN WATTS PER METER-DEGREE CENTIGRADE.

BEARING NUMBER	NUMBER OF ROLLING ELEMENTS	AZIMUTH ANGLE ORIENTATION	PITCH DIAMETER	DIAMETRAL CLEARANCE	CONTACT ANGLE	INNER RING SPEED	OUTER RING SPEED
1	14	-0.000	65.000	.060	-0.000	15000.	-0.
2	18	-0.000	140.000	-0.000	25.000	15000.	-0.

C A G E D A T A

BEARING NUMBER	CAGE TYPE	CAGE POCKET CLEARANCE	RAIL-LAND WIDTH	RAIL-LAND DIAMETER	RAIL-LAND CLEARANCE	WEIGHT
1	INNER RING LAND RIDING	.290000	2.6800	53.8880	.240	.050000
2	INNER RING LAND RIDING	.826000	4.0000	129.4700	1.270	.330000

S T E E L D A T A

BRG.NO.	INNER RING TYPE	LIFE FACTOR	OUTER RING TYPE	LIFE FACTOR
1	AISI 52100	3.000	AISI 52100	3.000
2	M50 CVM	5.000	M50 CVM	5.000

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R O L L I N G   E L E M E N T   D A T A

BEARING NUMBER (1) TYPE - CYLINDRICAL ROLLER BEARING

ROLLER DIAMETER	ROLLER LENGTH	ROLLER END SPHERE RADIUS	ROLLER INCL. ANGLE	AXIAL PLAY OUTER RING	AXIAL PLAY INNER RING	FLANGE ANGLE OUTER RING	FLANGE ANGLE INNER RING
10.0000	10.0000	200.0000	0.000	0.0000	0.0000	0.000	0.000

EFF.LENGTH	OUTER RACEWAY FLAT LENGTH	CROWN RAD.	EFF.LENGTH	INNER RACEWAY FLAT LENGTH	CROWN RAD.	NO. OF AXIAL LAMINAE
8.0000	3.0000	1000.000	8.0000	3.0000	1000.000	10

BEARING NUMBER (2) TYPE - BALL BEARING

BALL DIAMETER	OUTER RACEWAY CURVATURE	INNER RACEWAY CURVATURE
19.0500	.520	.540

BEST AVAILABLE COPY

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S U R F A C E D A T A

BEARING NUMBER	CLA ROUGHNESS OUTER	CLA ROUGHNESS INNER	CLA ROUGHNESS ROLL. ELM.	RMS ASPERITY SLOPE OUTER	RMS ASPERITY SLOPE INNER	RMS ASPERITY SLOPE ROLL. ELM.
1	.15	.15	.10	2.000	2.000	2.000
2	.08	.08	.04	2.000	2.000	2.000

L U B R I C A N T D A T A

BEARING NUMBER	DESIGNATION	KINEMATIC VISCOSITY (37.78 C)	KINEMATIC VISCOSITY (98.89 C)	DENSITY AT (15.56 C)	THERMAL EXPAN. COEFFICIENT	THERMAL CONDUCTIVITY
1	MIL-L-7808G	12.76	3.20	.9526	7.09E-04	.152
2	MIL-L-7808G	12.76	3.20	.9526	7.09E-04	.152

L U B R I C A T I O N A N D F R I C T I O N D A T A

BEARING NUMBER	PERCENT LUBE IN CAVITY	FILM REPLENISHMENT LAYER THICKNESS (ROLL.ELM. + RACEWAY) OUTER	FILM REPLENISHMENT LAYER THICKNESS (ROLL.ELM. + RACEWAY) INNER	ASPERITY FRICTION COEFFICIENT
1	1.00	.9000E-03	.3000E-03	.10
2	1.00	.6000E-03	.2000E-03	.10

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F I T D A T A A N D M A T E R I A L P R O P E R T I E S

BEARING NUMBER	COLD FITS (MM TIGHT) SHAFT	HOUSING	EFFECTIVE WIDTHS SHAFT	INNER RING	OUTER RING	HOUSING
1	.0380	-.0250	24.0000	19.0000	19.0000	22.0000
2	.0050	-.0380	22.0000	17.0000	34.0000	67.0000

EFFECTIVE DIAMETERS

BEARING NUMBER	SHAFT I.D.	BEARING BORE	INNER RING AVE. O.D.	OUTER RING AVE. I.D.	BEARING O.D.	HOUSING O.D.
1	1.000	45.000	54.000	73.000	85.000	120.000
2	20.000	100.000	127.000	155.000	180.000	205.000

BEARING NUMBER (1)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	204083.0
POISSONS RATIO	.3000	.3000	.3000	.3000	.3000
WEIGHT DENSITY	7.806	7.806	7.806	7.806	7.806
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00001224

BEARING NUMBER (2)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	204083.0
POISSONS RATIO	.3000	.3000	.3000	.3000	.3000
WEIGHT DENSITY	7.806	7.806	7.806	7.806	7.806
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00001224

UNLESS OTHERWISE STATED, INTERNATIONAL UNITS ARE USED

GIVEN TEMPERATURES

BRG	SHAFT	I. RING	I. RACE	ROLL EL.	O. RACE	O. RING	HOUSING	BULK	FLANGE
1	66.00	71.00	74.00	77.00	74.00	71.00	66.00	57.00	-0.00
2	177.00	182.00	185.00	189.00	188.00	185.00	177.00	141.00	-0.00

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SHAFT GEOMETRY, BEARING LOCATIONS AND SHAFT LOAD, PLANE X - Y.

20 GEOMETRIC SECTIONS 1 LOAD SECTION(S), 2 BEARINGS, MODULUS OF ELASTICITY = 2.041E+05

	POSI-	INNER DIAM.		OUTER DIAM.		POINT	POINT	LOAD INTENSITY			BEARING SEAT			
	TION	LEFT	RIGHT	LEFT	RIGHT	FORCE	MOMENT	LEFT	RIGHT		POS.ERR	DEFL/FOR	ANG.ERR	DEFL/MOM
1	0.0	0.0	0.0	0.0	29.0					1				
2	45.0	0.0	0.0	29.0	45.0					2				
3	54.0	0.0	0.0	45.0	45.0					3	-0.000	-0.	-0.0000	-0.
4	63.5	0.0	0.0	45.0	52.0					4				
5	69.0	0.0	0.0	52.0	52.0					5				
6	71.0	0.0	0.0	44.0	44.0					6				
7	73.0	0.0	0.0	42.0	42.0					7				
8	322.0	0.0	0.0	42.0	42.0					8				
9	324.0	0.0	0.0	44.0	44.0					9				
10	326.0	0.0	0.0	58.0	58.0					10				
11	340.0	0.0	0.0	58.0	85.0					11				
12	355.0	0.0	0.0	85.0	85.0	2224.1	-4000.0			12				
13	356.0	0.0	0.0	95.0	100.0					13				
14	378.0	0.0	0.0	100.0	41.5					14				
15	439.0	0.0	24.0	41.5	39.0					15				
16	441.0	28.0	28.0	38.0	38.0					16				
17	459.0	30.0	30.0	38.0	33.0					17				
18	461.0	30.0	30.0	41.5	41.5					18				
19	470.0	20.0	20.0	41.5	41.5					19				
20	480.0	20.0	20.0	41.5	116.0					20				
21	487.0	20.0	20.0	116.0	100.0					21				
22	504.0	20.0	20.0	100.0	100.0					22	-0.000	-0.	-0.0000	-0.
23	524.0	20.0	20.0	100.0	100.0					23				

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BEARING SYSTEM OUTPUT METRIC UNITS

	LINEAR (MM) AND ANGULAR (RADIANS) DEFLECTIONS					REACTION FORCES (N) AND MOMENTS (MM-N)				
BRG.	DX	DY	DZ	GY	GZ	FX	FY	FZ	MY	MZ
1	5.565E-03	2.016E-02	-1.874E-09	8.940E-13	8.166E-05	0.	741.	.574	2.070E-03	48.8
2	5.565E-03	-7.335E-03	-9.457E-10	-7.850E-12	-3.414E-04	9.074E+03	1.477E+03	14.2	657.	-7.323E+04

	FATIGUE LIFE (HOURS)			H/SIGMA		LUBE-LIFE FACTOR		MATERIAL FACTOR	
BRG.	O. RACE	I. RACE	BEARING	O. RACE	I. RACE	O. RACE	I. RACE	O. RACE	I. RACE
1	2.637E+06	1.286E+06	9.268E+05	1.86	1.66	.645	.582	3.00	3.00
2	2.519E+03	2.223E+03	1.265E+03	1.52	1.37	.542	.505	5.00	5.00

TEMPERATURES RELEVANT TO BEARING PERFORMANCE (DEGREES CENTIGRADE)

BRG.	SHAFT	I. RING	I. RACE	I. FLNG.	ROLL. EL.	O. FLNG.	O. RACE	O. RING	HSG.	BULK LUBE
1	66.0	71.0	74.0	74.0	77.0	74.0	74.0	71.0	66.0	57.0
2	177.	182.	185.	185.	189.	188.	188.	185.	177.	141.

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B E A R I N G   S Y S T E M   O U T P U T   METRIC UNITS

FRICTIONAL HEAT GENERATION RATE (WATTS) AND FRICTION TORQUE (N-MM)

BRG.	O. RACE	O. FLNGS.	I. RACE	I. FLNGS.	R.E.DRAG	R.E.-CAGE	CAGE-LAND	TOTAL	TORQUE
1	224.	0.	44.8	0.	64.5	19.7	40.1	394.	251.
2	601.	0.	607.	0.	782.	22.8	23.8	2.037E+03	1.297E+03

EHD FILM THICKNESS, FILM REDUCTION FACTORS AND HEAT CONDUCTIVITY DATA FOR THE OUTER AND INNER RACEWAYS RESPECTIVELY

BRG.	FILM (MICRONS)		STARVATION FACTOR		THERMAL FACTOR		MENISCUS DIST. (MM)		CONDUCTIVITY (W/DEG.C)	
1	.302	.269	1.00	.998	.925	.925	1.17	.509	2.36	.760
2	.117	.105	.998	.986	.947	.960	.647	.250	31.3	16.7

	FIT PRESSURES (N/MM2)				BEARING CLEARANCES (MM)			SPEED GIVING ZERO FIT PRESSURE
BRG.	SHAFT-COLD,	OPER.	HSG.-COLD,	OPER.	ORIGINAL	CHANGE	OPERATING	SHAFT-INNER RING (RPM)
1	26.9	23.2	0.	0.	6.000E-02	-3.165E-02	2.835E-02	5.575E+04
2	1.97	0.	0.	0.	0.	-2.281E-02	-2.281E-02	3.957E+03

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B E A R I N G   S Y S T E M   O U T P U T   METRIC UNITS

LUBRICANT TEMPERATURES AND PHYSICAL PROPERTIES

	LOCATION	TEMPERATURES (DEGREES C.)	DENSITY (GM/CM3)	VISCOSITY KINEMATIC (CS)	VISCOSITY DYNAMIC (CP)	PRESSURE VISCOSITY COEFFICIENT (MM2/N)
BRG. 1	OUTER	74.000	.9112	5.010	4.565	.1189E-01
	INNER	74.000	.9112	5.010	4.565	.1189E-01
	BULK	57.000	.9232	7.377	6.810	.1322E-01
BRG. 2	OUTER	188.000	.8303	1.228	1.020	.5941E-02
	INNER	185.000	.8324	1.255	1.045	.6060E-02
	BULK	141.000	.8636	1.855	1.602	.8100E-02

C A G E   D A T A   METRIC UNITS

	CAGE RAIL - RING LAND DATA				CAGE SPEED DATA					
BRG.	TORQUE (MM-N)	HEAT RATE (WATTS)	SEP.FORCE (NEWTONS)	ECCENTRICITY RATIO	EPICYCLIC SPEED (RAD/SEC)	EPICYCLIC SPEED (RPM)	CALCULATED SPEED (RAD/SEC)	CALCULATED SPEED (RPM)	CALC/EPIC RATIO	CAGE/SHAFT RATIO
1	44.2	40.1	0.	0.	665.	6.346E+03	664.	6.342E+03	.999	.423
2	28.3	23.8	0.	0.	731.	6.981E+03	729.	6.962E+03	.997	.464

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R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 1 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)					SPEED VECTOR ANGLES (DEGREES)	
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
0.00	-4985.252	-.159	0.000	4985.252	664.239	-180.00	180.00
25.71	-4985.375	-.098	0.000	4985.375	664.077	-180.00	180.00
51.43	-4988.160	0.000	0.000	4988.160	663.630	180.00	180.00
77.14	-4978.986	0.000	0.000	4978.986	662.592	180.00	180.00
102.86	-4988.216	0.000	0.000	4988.216	664.124	180.00	180.00
128.57	-4990.272	0.000	0.000	4990.272	664.435	180.00	180.00
154.29	-5000.465	0.000	0.000	5000.465	665.500	180.00	180.00
180.00	-4992.588	0.000	0.000	4992.588	664.135	180.00	180.00
205.71	-4991.293	0.000	0.000	4991.293	663.892	180.00	180.00
231.43	-4980.645	0.000	0.000	4980.645	662.727	180.00	180.00
257.14	-4988.110	0.000	0.000	4988.110	664.002	180.00	180.00
282.86	-4988.086	0.000	0.000	4988.086	664.150	180.00	180.00
308.57	-5000.599	0.000	0.000	5000.599	665.408	180.00	180.00
334.29	-4986.118	-.098	0.000	4986.118	664.351	-180.00	180.00

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WPAFB LUBRICATION BRANCH * R.E.B. TEST MACHINE ASSEMBLY I * SOLUTION LEVEL 2

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 1 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
0.00	-.081	463.758	375.831	864.714	871.402	.0520	.0768	0.00	0.00
25.71	-.102	290.537	202.677	663.352	673.547	.0512	.0761	0.00	0.00
51.43	-.029	87.948	0.000	406.601	0.000	.0440	0.0000	0.00	0.00
77.14	.277	87.493	0.000	405.573	0.000	.0442	0.0000	0.00	0.00
102.86	.520	87.903	0.000	406.281	0.000	.0439	0.0000	0.00	0.00
128.57	.456	87.934	0.000	406.421	0.000	.0438	0.0000	0.00	0.00
154.29	.172	88.260	0.000	406.898	0.000	.0435	0.0000	0.00	0.00
180.00	-.055	87.895	0.000	406.267	0.000	.0438	0.0000	0.00	0.00
205.71	-.031	87.830	0.000	406.155	0.000	.0439	0.0000	0.00	0.00
231.43	.212	87.527	0.000	405.630	0.000	.0442	0.0000	0.00	0.00
257.14	.448	87.869	0.000	406.222	0.000	.0439	0.0000	0.00	0.00
282.86	.453	87.908	0.000	406.291	0.000	.0439	0.0000	0.00	0.00
308.57	.229	88.425	0.000	407.422	0.000	.0436	0.0000	0.00	0.00
334.29	-.018	290.575	202.641	663.390	673.499	.0511	.0762	0.00	0.00

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WPAFB LUBRICATION BRANCH * R.E.B. TEST MACHINE ASSEMBLY I * SOLUTION LEVEL 2

R O L L I N G E L E M E N T O U T P U T FOR BEARING NUMBER 2 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)					SPEED VECTOR ANGLES (DEGREES)	
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
0.00	-6279.481	182.321	-38.747	6282.247	728.668	178.34	-179.65
20.00	-6281.129	186.768	-40.295	6284.034	728.800	178.30	-179.63
40.00	-6277.956	188.121	-41.730	6280.912	728.984	178.28	-179.62
60.00	-6270.635	186.271	-42.886	6273.548	729.199	178.30	-179.61
80.00	-6260.268	181.644	-43.620	6263.054	729.413	178.34	-179.60
100.00	-6248.235	174.871	-43.780	6250.835	729.588	178.40	-179.60
120.00	-6236.013	166.911	-43.300	6238.397	729.686	178.47	-179.60
140.00	-6224.970	158.674	-42.192	6227.134	729.695	178.54	-179.61
160.00	-6216.102	151.073	-40.599	6218.070	729.613	178.61	-179.63
180.00	-6210.338	144.860	-38.766	6212.148	729.466	178.66	-179.64
200.00	-6208.115	140.661	-36.956	6209.818	729.282	178.70	-179.66
220.00	-6209.970	138.969	-35.452	6211.625	729.101	178.72	-179.67
240.00	-6215.752	139.997	-34.430	6217.424	728.933	178.71	-179.68
260.00	-6225.147	143.754	-33.974	6226.899	728.794	178.68	-179.69
280.00	-6237.220	150.027	-34.123	6239.118	728.691	178.62	-179.69
300.00	-6250.454	158.061	-34.789	6252.549	728.630	178.55	-179.68
320.00	-6263.035	166.916	-35.867	6265.362	728.595	178.47	-179.67
340.00	-6273.241	175.406	-37.235	6275.803	728.612	178.40	-179.66

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WPAFB LUBRICATION BRANCH * R.E.B. TEST MACHINE ASSEMBLY I * SOLUTION LEVEL 2

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 2 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
0.00	.151	2154.726	1189.237	1564.349	1652.950	.0675	.0886	16.64	31.49
20.00	.169	2141.116	1174.570	1561.049	1646.126	.0674	.0887	16.51	31.45
40.00	.179	2102.111	1132.959	1551.511	1626.453	.0674	.0891	16.14	31.31
60.00	.179	2045.274	1072.319	1537.400	1596.901	.0674	.0897	15.53	31.10
80.00	.168	1980.338	1002.965	1520.954	1561.673	.0674	.0906	14.90	30.34
100.00	.148	1916.554	934.578	1504.447	1525.370	.0675	.0915	14.20	30.54
120.00	.123	1861.069	875.085	1489.766	1492.291	.0675	.0923	13.55	30.26
140.00	.095	1813.611	829.610	1478.370	1465.930	.0676	.0930	13.04	30.02
160.00	.071	1791.876	801.163	1471.389	1449.029	.0677	.0935	12.71	29.86
180.00	.052	1782.256	791.244	1468.452	1443.024	.0679	.0937	12.59	29.81
200.00	.040	1790.240	800.334	1470.641	1448.529	.0679	.0937	12.71	29.86
220.00	.037	1815.656	828.094	1477.568	1465.087	.0680	.0933	13.05	30.02
240.00	.040	1857.296	873.118	1488.779	1491.172	.0680	.0928	13.57	30.25
260.00	.050	1912.540	932.441	1503.396	1524.207	.0680	.0920	14.22	30.54
280.00	.065	1976.640	1000.881	1520.007	1560.621	.0679	.0911	14.92	30.83
300.00	.084	2042.307	1070.641	1536.656	1596.068	.0678	.0902	15.59	31.09
320.00	.106	2100.058	1131.771	1551.006	1625.884	.0677	.0895	16.15	31.31
340.00	.129	2140.107	1173.970	1560.804	1645.846	.0676	.0889	16.52	31.45

```
 CSA     NOS/BE L414C        6600 CMR1 07/31/76
03.12.16.BC1AERA  FROM
03.12.16.IP  00000960 WORDS - FILE INPUT   , DC 00
03.12.16.BC1AE,T1500,IO900,CM200000,STCSA. P74058
03.12.16.0 CRECELIUS
03.12.17.ATTACH,FILEMAN,ID=P720611.
03.12.17.PFN IS
03.12.17.FILEMAN
03.12.17.PF CYCLE NO. = 001
03.12.17.FILEMAN.
03.12.18.
03.12.18.****************************************
03.12.18.AFAPL PERM FILE SUPPORT PACKAGE  V2.1
03.12.18.
03.12.18. PURGE,XX,BILL,CY=2.
03.12.19.FILE NOT CATALOGED ON THIS SN. **
03.12.19. PURGE,YY,BILL,CY=3.
03.12.19.FILE NOT CATALOGED ON THIS SN. **
03.12.19. RETURN,XX.
03.12.19.FUNCTION SUCCESSFUL.
03.12.19. RETURN,YY.
03.12.19.FUNCTION SUCCESSFUL.
03.12.19.
03.12.19.CONTROL RETURNED TO NOS
03.12.19.****************************************
03.12.19.
03.12.19.     STOP
03.12.19.       .027 CP SECONDS EXECUTION TIME
03.12.19.ATTACH,OLDPL,BILL,CY=1.
03.12.19.UPDATE,P,F.
03.12.49. UPDATE COMPLETE.
03.12.49.FTN,I=COMPILE,L=0,PL=15000.
03.19.49.      53.023 CP SECONDS COMPILATION TIME
03.19.50.MAP,CN.
03.19.50.SEGLOAD.
03.19.50.LOAD,LGO.
03.19.50.EXECUTE.
03.24.50.      END  SHABTH
03.24.50.OP  00027264 WORDS - FILE OUTPUT , DC 40
03.24.50.MS  275968  WORDS  ( 275968 MAX USED)
03.24.50.SCM 164000  WORDS MAXIMUM
03.24.50.CPA     111.881 SEC.        40.254 ADJ.
03.24.50.IO      105.327 SEC.        57.066 ADJ.
03.24.50.CM     6456.629 KWS.        77.556 ADJ.
03.24.50.CRUS                       174.878
03.24.50.COST                 $      10.49
03.24.50.PP     237.362 SEC.      DATE 07/22/76
03.24.50.EJ  END OF JOB, **  P740580.

***********          BC1AERA  //// END OF LIST ////
***********          BC1AERA  //// END OF LIST ////
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APPENDIX II

CH-53 POWER INPUT MODULE - STEADY STATE LUBRICATED ANALYSIS

SHABERTH OUTPUT

*** S H A B E R T H / A B R ** TECHNOLOGY DIVISION S K F INDUSTRIES INC. ** S H A B E R T H / A B R ***

CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

THIS DATA SET CONTAINS 5 BEARINGS

BEARING NO. (1) - CYLINDRICAL ROLLER BEARING

BEARING NO. (2) - BALL BEARING

BEARING NO. (3) - BALL BEARING

BEARING NO. (4) - BALL BEARING

BEARING NO. (5) - BALL BEARING

THE MAXIMUM NUMBER OF FIT ITERATIONS ALLOWED IS 2 AND THE RELATIVE ACCURACY REQUIRED IS .00010

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

UNLESS OTHERWISE STATED, LINEAR DIMENSIONS ARE SPECIFIED IN MILLIMETERS, TEMPERATURES IN DEGREES CENTIGRADE, FORCES IN NEWTONS, WEIGHTS IN KILOGRAMS, PRESSURES AND ELASTIC MODULI IN NEWTONS PER SQUARE MILLIMETER, ANGLES AND SLOPES IN DEGREES, SURFACE ROUGHNESS IN MICRONS, SPEEDS IN REVOLUTIONS PER MINUTE, DENSITY IN GRAMS PER CUBIC CENTIMETER, KINEMATIC VISCOSITY IN CENTISTOKES AND THERMAL CONDUCTIVITY IN WATTS PER METER-DEGREE CENTIGRADE.

BEARING NUMBER	NUMBER OF ROLLING ELEMENTS	AZIMUTH ANGLE ORIENTATION	PITCH DIAMETER	DIAMETRAL CLEARANCE	CONTACT ANGLE	INNER RING SPEED	OUTER RING SPEED
1	16	.000	110.000	.038	.000	13600.	0.
2	15	.000	110.000	.022	23.000	13600.	0.
3	15	.000	110.000	.022	23.000	13600.	0.
4	15	.000	110.000	.022	23.000	13600.	0.
5	15	.000	110.000	.022	-23.000	13600.	0.

C A G E D A T A

BEARING NUMBER	CAGE TYPE	CAGE POCKET CLEARANCE	RAIL-LAND WIDTH	RAIL-LAND DIAMETER	RAIL-LAND CLEARANCE	WEIGHT
1	OUTER RING LAND RIDING	.952500	2.7500	120.3000	1.420	.200000
2	INNER RING LAND RIDING	.952500	2.8800	102.0000	.635	.180000
3	INNER RING LAND RIDING	.952500	2.8800	102.0000	.635	.180000
4	INNER RING LAND RIDING	.952500	2.8800	102.0000	.635	.180000
5	INNER RING LAND RIDING	.952500	2.8800	102.0000	.635	.180000

S T E E L D A T A

BRG.NO.	INNER RING TYPE	LIFE FACTOR	OUTER RING TYPE	LIFE FACTOR
1	M-50	5.000	M-50	5.000
2	M-50	5.000	M-50	5.000
3	M-50	5.000	M-50	5.000
4	M-50	5.000	M-50	5.000
5	M-50	5.000	M-50	5.000

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

R O L L I N G   E L E M E N T   D A T A

BEARING NUMBER (1)   TYPE - CYLINDRICAL ROLLER BEARING

ROLLER DIAMETER	ROLLER LENGTH	ROLLER END SPHERE RADIUS	ROLLER INCL. ANGLE	AXIAL PLAY OUTER RING	AXIAL PLAY INNER RING	FLANGE ANGLE OUTER RING	FLANGE ANGLE INNER RING
17.0000	19.0000	1000.0000	.000	.0000	.0000	.000	.000

OUTER RACEWAY EFF.LENGTH	OUTER RACEWAY FLAT LENGTH	OUTER RACEWAY CROWN RAD.	INNER RACEWAY EFF.LENGTH	INNER RACEWAY FLAT LENGTH	INNER RACEWAY CROWN RAD.	NO. OF AXIAL LAMINAE
17.0000	8.7500	1524.000	17.0000	8.7500	1524.000	10

BEARING NUMBER (2)   TYPE - BALL BEARING

BALL DIAMETER	OUTER RACEWAY CURVATURE	INNER RACEWAY CURVATURE
19.0500	.515	.520

BEARING NUMBER (3)   TYPE - BALL BEARING

BALL DIAMETER	OUTER RACEWAY CURVATURE	INNER RACEWAY CURVATURE
19.0500	.515	.520

BEARING NUMBER (4)   TYPE - BALL BEARING

BALL DIAMETER	OUTER RACEWAY CURVATURE	INNER RACEWAY CURVATURE
19.0500	.515	.520

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

ROLLING ELEMENT DATA

BEARING NUMBER (5) TYPE - BALL BEARING

BALL DIAMETER	OUTER RACEWAY CURVATURE	INNER RACEWAY CURVATURE
19.0500	.515	.520

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

S U R F A C E D A T A

BEARING NUMBER	CLA ROUGHNESS OUTER	CLA ROUGHNESS INNER	CLA ROUGHNESS ROLL. ELM.	RMS ASPERITY SLOPE OUTER	RMS ASPERITY SLOPE INNER	RMS ASPERITY SLOPE ROLL. ELM.
1	.20	.20	.20	2.000	2.000	2.000
2	.15	.15	.15	2.000	2.000	2.000
3	.15	.15	.15	2.000	2.000	2.000
4	.15	.15	.15	2.000	2.000	2.000
5	.15	.15	.15	2.000	2.000	2.000

L U B R I C A N T D A T A

BEARING NUMBER	DESIGNATION	KINEMATIC VISCOSITY (37.78 C)	KINEMATIC VISCOSITY (98.89 C)	DENSITY AT (15.56 C)	THERMAL EXPAN. COEFFICIENT	THERMAL CONDUCTIVITY
1	MIL-L-7808G	12.76	3.20	.9526	7.09-04	.152
2	MIL-L-7808G	12.76	3.20	.9526	7.09-04	.152
3	MIL-L-7808G	12.76	3.20	.9526	7.09-04	.152
4	MIL-L-7808G	12.76	3.20	.9526	7.09-04	.152
5	MIL-L-7808G	12.76	3.20	.9526	7.09-04	.152

L U B R I C A T I O N A N D F R I C T I O N D A T A

BEARING NUMBER	PERCENT LUBE IN CAVITY	FILM REPLENISHMENT LAYER THICKNESS (ROLL.ELM. + RACEWAY) OUTER	FILM REPLENISHMENT LAYER THICKNESS (ROLL.ELM. + RACEWAY) INNER	ASPERITY FRICTION COEFFICIENT
1	.75	.3000-03	.1000-03	.10
2	.75	.1500-02	.5000-03	.10
3	1.50	.3000-02	.1000-02	.10
4	1.50	.3000-02	.1000-02	.10
5	1.50	.3000-02	1000-02	.10

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CH-53 POWER INPUT MODULE -STEADY STATE LUBRICATED ANALYSIS- 1450 SHP WP 7/76

F I T D A T A A N D M A T E R I A L P R O P E R T I E S

BEARING NUMBER	COLD FITS (MM TIGHT) SHAFT	HOUSING	EFFECTIVE WIDTHS SHAFT	INNER RING	OUTER RING	HOUSING
1	.0380	-.0076	50.0000	26.0000	26.0000	50.0000
2	.0203	-.0076	40.0000	26.0000	26.0000	40.0000
3	.0203	-.0076	26.0000	26.0000	26.0000	26.0000
4	.0203	-.0076	26.0000	26.0000	26.0000	26.0000
5	.0203	-.0076	40.0000	26.0000	26.0000	40.0000

BEARING NUMBER	SHAFT I.D.	BEARING BORE	EFFECTIVE DIAMETERS INNER RING AVE. O.D.	OUTER RING AVE. I.D.	BEARING O.D.	HOUSING O.D.
1	64.000	80.000	93.000	127.000	140.000	184.000
2	64.000	80.000	99.070	124.170	140.000	184.000
3	64.000	80.000	99.070	124.170	140.000	184.000
4	64.000	80.000	99.070	124.170	140.000	184.000
5	56.000	80.000	99.070	124.170	140.000	184.000

BEARING NUMBER (1)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	41368.9
POISSONS RATIO	.3000	.3000	.3000	.3000	.3500
WEIGHT DENSITY	7.806	7.806	7.806	7.806	1.770
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00002520

BEARING NUMBER (2)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	41368.9
POISSONS RATIO	.3000	.3000	.3000	.3000	.3500
WEIGHT DENSITY	7.806	7.806	7.806	7.806	1.770
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00002520

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

BEARING NUMBER (3)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	41368.9
POISSONS RATIO	.3000	.3000	.3000	.3000	.3500
WEIGHT DENSITY	7.806	7.806	7.806	7.806	1.770
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00002520

BEARING NUMBER (4)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	41368.9
POISSONS RATIO	.3000	.3000	.3000	.3000	.3500
WEIGHT DENSITY	7.806	7.806	7.806	7.806	1.770
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00002520

BEARING NUMBER (5)	SHAFT	INNER RING	ROLL. ELEM.	OUTER RING	HOUSING
MODULUS OF ELASTICITY	204083.0	204083.0	204083.0	204083.0	41368.9
POISSONS RATIO	.3000	.3000	.3000	.3000	.3500
WEIGHT DENSITY	7.806	7.806	7.806	7.806	1.770
COEFF. OF THERMAL EXP.	.00001224	.00001224	.00001224	.00001224	.00002520

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

STEADY STATE TEMPERATURE CALCULATION, ITERATION LIMIT 10, ABSOLUTE ACCURACY 1.00 DEGREES
INTERMEDIATE OUTPUT WILL BE OBTAINED

UNLESS OTHERWISE STATED, INTERNATIONAL UNITS ARE USED

NODE POINTERS

BRG	SHAFT	I. RING	I. RACE	ROLL EL.	O. RACE	O. RING	HOUSING	BULK	FLANGE
1	4	5	5	6	7	7	8	41	0
2	13	14	14	15	16	16	17	43	0
3	19	20	20	21	22	22	23	46	0
4	24	25	25	26	27	27	28	49	0
5	31	32	32	33	34	34	35	52	0

NODES WHERE BEARING HEAT IS GENERATED

BRG	INNER RACE		OUTER RACE		CAGE		DRAG		FLANGE	
1	5	6	6	7	7	7	6	41	0	0
2	14	15	15	16	14	14	15	43	0	0
3	20	21	21	22	20	20	21	46	0	0
4	25	26	26	27	25	25	26	49	0	0
5	32	33	33	34	32	32	33	52	0	0

CONSTANT GENERATED HEATS

NODE	GEN. HEAT	NODE	GEN. HEAT	NODE	GEN. HEAT	NODE	GEN. HEAT	NODE	GEN. HEAT
10	2500.00	37	100.00	58	2500.00				

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

HEAT TRANSFER COEFFICIENTS

TYPE	INDEX	COEFFICIENTS				
CONDUCTION	1	53.6517				
CONDUCTION	2	46.7289				
CONDUCTION	3	50.8291				
FORCED CONVECTION	21	.300000	.570000	.000000	.180000-01	34.0000
		.170000	.000000	900.000	2000.00	25.0000
		.180000-01	218.330	.700000-03	103.434	.421460+11
		-4.09921	.900000-03	-.570000		
FORCED CONVECTION	22	.300000	.570000	.000000	.250000-01	48.0000
		.280000-01	.220000-04	1.21000	1000.00	.000000
		.000000	.000000	.000000	187.707	.000000
		.000000	.000000	.000000		
FORCED CONVECTION	23	37.0000				
FORCED CONVECTION	24	5000.00				
FORCED CONVECTION	25	.270000-01	.800000	.333000	.500000-03	40.0000
		.170000	.000000	900.000	2000.00	25.0000
		.180000-01	218.330	.700000-03	2101.67	.421460+11
		-4.09921	.900000- 3	-.467000		
FORCED CONVECTION	26	.300000	.570000	.000000	.250000-01	48.0000
		.170000	.000000	900.000	2000.00	25.0000
		.180000-01	218.330	.700000-03	109.315	.421460+11
		-4.09921	.900000-03	-.570000		
FLUID FLOW	41	28.0000				
FLUID FLOW	42	42.0000				
FLUID FLOW	43	21.0000				
FLUID FLOW	44	63.0000				

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CH-53 POWER INPUT MODULE -STEADY STATE LUBRICATED ANALYSIS- 1450 SHP WP 7/76

HEAT TRANSFER COEFFICIENTS

TYPE	INDEX	COEFFICIENTS
FLUID FLOW	45	105.000
FLUID FLOW	46	147.000
FLUID FLOW	47	332.000
FLUID FLOW	48	136.000

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

DESCRIPTION OF THE GEOMETRY AND INDICATION OF THE TYPES AND PATHS OF HEAT TRANSFER

ALL LENGTHS ARE IN MILLIMETERS. A NEGATIVE SIGN OF THE INDEX MEANS NO ROTATIONAL SYMMETRY

TYPE OF HEAT TR.	INDEX		NODE		NODE	1ST LENGTH	2ND LENGTH	3RD LENGTH
CONDUCTION	1	BETWEEN	1	AND	2	60.0000	24.0000	44.0000
CONDUCTION	-1	BETWEEN	2	AND	3	20.0000	140.0000	150.0000
CONDUCTION	1	BETWEEN	4	AND	8	77.0000	26.0000	84.0000
CONDUCTION	1	BETWEEN	8	AND	12	96.0000	6.0000	70.0000
CONDUCTION	1	BETWEEN	12	AND	18	100.0000	6.0000	74.0000
CONDUCTION	1	BETWEEN	18	AND	29	104.0000	20.0000	53.0000
CONDUCTION	-1	BETWEEN	29	AND	30	20.0000	140.0000	150.0000
CONDUCTION	1	BETWEEN	29	AND	36	104.0000	22.0000	26.0000
CONDUCTION	1	BETWEEN	29	AND	28	92.0000	26.0000	22.0000
CONDUCTION	1	BETWEEN	36	AND	35	92.0000	26.0000	22.0000
CONDUCTION	1	BETWEEN	36	AND	39	104.0000	22.0000	26.0000
CONDUCTION	1	BETWEEN	39	AND	38	92.0000	26.0000	22.0000
CONDUCTION	1	BETWEEN	3	AND	30	170.0000	6.0000	276.0000
CONDUCTION	1	BETWEEN	17	AND	23	81.0000	22.0000	26.0000
CONDUCTION	1	BETWEEN	23	AND	28	81.0000	22.0000	26.0000
CONDUCTION	1	BETWEEN	28	AND	35	81.0000	22.0000	26.0000
CONDUCTION	1	BETWEEN	35	AND	38	81.0000	22.0000	26.0000
CONDUCTION	2	BETWEEN	8	AND	7	70.0000	26.0000	10.0000
CONDUCTION	2	BETWEEN	17	AND	16	74.0000	26.0000	13.0000
CONDUCTION	2	BETWEEN	23	AND	22	74.0000	26.0000	13.0000
CONDUCTION	2	BETWEEN	28	AND	27	74.0000	26.0000	13.0000
CONDUCTION	2	BETWEEN	35	AND	34	74.0000	26.0000	13.0000
CONDUCTION	3	BETWEEN	4	AND	5	40.0000	26.0000	7.0000
CONDUCTION	3	BETWEEN	4	AND	9	36.0000	5.0000	36.0000
CONDUCTION	3	BETWEEN	9	AND	10	56.0000	12.0000	40.0000

CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

DESCRIPTION OF THE GEOMETRY AND INDICATION OF THE TYPES AND PATHS OF HEAT TRANSFER

ALL LENGTHS ARE IN MILLIMETERS, A NEGATIVE SIGN OF THE INDEX MEANS NO ROTATIONAL SYMMETRY

TYPE OF HEAT TR.	INDEX		NODE		NODE	1ST LENGTH	2ND LENGTH	3RD LENGTH
CONDUCTION	3	BETWEEN	10	AND	11	58.0000	14.0000	44.0000
CONDUCTION	3	BETWEEN	5	AND	9	43.0000	3.0000	36.0000
CONDUCTION	3	BETWEEN	11	AND	14	42.0000	5.0000	36.0000
CONDUCTION	3	BETWEEN	11	AND	13	38.0000	7.0000	36.0000
CONDUCTION	3	BETWEEN	13	AND	14	40.0000	26.0000	8.0000
CONDUCTION	3	BETWEEN	13	AND	19	36.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	14	AND	20	43.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	19	AND	20	40.0000	26.0000	8.0000
CONDUCTION	3	BETWEEN	16	AND	22	66.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	22	AND	27	66.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	20	AND	25	43.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	19	AND	24	36.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	24	AND	25	40.0000	26.0000	8.0000
CONDUCTION	3	BETWEEN	27	AND	34	66.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	25	AND	32	43.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	24	AND	31	36.0000	8.0000	26.0000
CONDUCTION	3	BETWEEN	31	AND	32	40.0000	26.0000	8.0000
CONDUCTION	3	BETWEEN	31	AND	37	40.0000	8.0000	40.0000
CONDUCTION	3	BETWEEN	32	AND	37	46.0000	6.0000	32.0000
FORCED CONVECTION	21	BETWEEN	5	AND	41	46.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	6	AND	41	17.0000	220.0000	
FORCED CONVECTION	21	BETWEEN	7	AND	41	63.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	14	AND	43	46.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	15	AND	43	142.5000	19.0000	
FORCED CONVECTION	21	BETWEEN	16	AND	43	63.0000	26.0000	

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

DESCRIPTION OF THE GEOMETRY AND INDICATION OF THE TYPES AND PATHS OF HEAT TRANSFER

ALL LENGTHS ARE IN MILLIMETERS. A NEGATIVE SIGN OF THE INDEX MEANS NO ROTATIONAL SYMMETRY

TYPE OF HEAT TR.	INDEX		NODE		NODE	1ST LENGTH	2ND LENGTH	3RD LENGTH
FORCED CONVECTION	21	BETWEEN	20	AND	46	46.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	21	AND	46	142.5000	19.0000	
FORCED CONVECTION	21	BETWEEN	22	AND	46	63.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	25	AND	49	46.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	26	AND	49	142.5000	19.0000	
FORCED CONVECTION	21	BETWEEN	27	AND	49	63.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	32	AND	52	46.0000	26.0000	
FORCED CONVECTION	21	BETWEEN	33	AND	52	142.5000	19.0000	
FORCED CONVECTION	21	BETWEEN	34	AND	52	63.0000	26.0000	
FORCED CONVECTION	22	BETWEEN	1	AND	40	46.0000	23.0000	
FORCED CONVECTION	22	BETWEEN	2	AND	40	60.0000	20.0000	
FORCED CONVECTION	22	BETWEEN	3	AND	40	70.0000	140.0000	
FORCED CONVECTION	22	BETWEEN	4	AND	40	40.0000	60.0000	
FORCED CONVECTION	22	BETWEEN	8	AND	40	60.0000	40.0000	
FORCED CONVECTION	22	BETWEEN	9	AND	40	40.0000	40.0000	
FORCED CONVECTION	22	BETWEEN	10	AND	40	66.0000	100.0000	
FORCED CONVECTION	22	BETWEEN	11	AND	40	42.0000	30.0000	
FORCED CONVECTION	22	BETWEEN	12	AND	40	96.0000	100.0000	
FORCED CONVECTION	22	BETWEEN	17	AND	40	80.0000	40.0000	
FORCED CONVECTION	22	BETWEEN	18	AND	40	110.0000	20.0000	
FORCED CONVECTION	22	BETWEEN	29	AND	40	120.0000	10.0000	
FORCED CONVECTION	22	BETWEEN	30	AND	40	80.0000	130.0000	
FORCED CONVECTION	23	BETWEEN	1	AND	60	46.0000	23.0000	
FORCED CONVECTION	25	BETWEEN	42	AND	13	32.0000	5.0000	
FORCED CONVECTION	25	BETWEEN	45	AND	19	32.0000	5.0000	

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

DESCRIPTION OF THE GEOMETRY AND INDICATION OF THE TYPES AND PATHS OF HEAT TRANSFER

ALL LENGTHS ARE IN MILLIMETERS. A NEGATIVE SIGN OF THE INDEX MEANS NO ROTATIONAL SYMMETRY

TYPE OF HEAT TR.	INDEX		NODE		NODE	1ST LENGTH	2ND LENGTH	3RD LENGTH
FORCED CONVECTION	25	BETWEEN	46	AND	24	32.0000	5.0000	
FORCED CONVECTION	25	BETWEEN	51	AND	31	32.0000	5.0000	
FORCED CONVECTION	26	BETWEEN	10	AND	58	66.0000	100.0000	
FORCED CONVECTION	23	BETWEEN	2	AND	60	80.0000	20.0000	
FORCED CONVECTION	23	BETWEEN	3	AND	60	70.0000	160.0000	
FORCED CONVECTION	23	BETWEEN	29	AND	60	120.0000	10.0000	
FORCED CONVECTION	23	BETWEEN	30	AND	60	80.0000	160.0000	
FORCED CONVECTION	23	BETWEEN	36	AND	60	110.0000	30.0000	
FORCED CONVECTION	23	BETWEEN	38	AND	60	82.0000	20.0000	
FORCED CONVECTION	23	BETWEEN	39	AND	60	110.0000	45.0000	
FORCED CONVECTION	23	BETWEEN	12	AND	60	110.0000	50.0000	
FORCED CONVECTION	23	BETWEEN	8	AND	60	100.0000	60.0000	
FORCED CONVECTION	23	BETWEEN	18	AND	60	50.0000	25.0000	
FORCED CONVECTION	24	BETWEEN	12	AND	57	96.0000	100.0000	
FLUID FLOW	41	FROM	61	TO	41	(INDEX 41)		
FLUID FLOW	41	FROM	41	TO	57	(INDEX 47)		
FLUID FLOW	42	FROM	61	TO	42	(INDEX 42)		
FLUID FLOW	42	FROM	61	TO	45	(INDEX 42)		
FLUID FLOW	42	FROM	61	TO	48	(INDEX 42)		
FLUID FLOW	42	FROM	61	TO	51	(INDEX 42)		
FLUID FLOW	42	FROM	42	TO	43	(INDEX 42)		
FLUID FLOW	42	FROM	45	TO	46	(INDEX 42)		
FLUID FLOW	42	FROM	48	TO	49	(INDEX 42)		
FLUID FLOW	42	FROM	51	TO	52	(INDEX 42)		
FLUID FLOW	42	FROM	43	TO	44	(INDEX 43)		

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ALL LENGTHS ARE IN MILLIMETERS. A NEGATIVE SIGN OF THE INDEX MEANS NO ROTATIONAL SYMMETRY

TYPE OF HEAT TR.	INDEX		NODE		NODE	1ST LENGTH	2ND LENGTH	3RD LENGTH
FLUID FLOW	43	FROM	43	TO	57	(INDEX 47)		
FLUID FLOW	42	FROM	46	TO	44	(INDEX 43)		
FLUID FLOW	42	FROM	46	TO	47	(INDEX 43)		
FLUID FLOW	42	FROM	49	TO	47	(INDEX 43)		
FLUID FLOW	42	FROM	49	TO	50	(INDEX 43)		
FLUID FLOW	42	FROM	52	TO	50	(INDEX 43)		
FLUID FLOW	42	FROM	52	TO	53	(INDEX 43)		
FLUID FLOW	42	FROM	47	TO	55	(INDEX 45)		
FLUID FLOW	43	FROM	53	TO	54	(INDEX 44)		
FLUID FLOW	42	FROM	50	TO	54	(INDEX 44)		
FLUID FLOW	44	FROM	54	TO	55	(INDEX 45)		
FLUID FLOW	42	FROM	44	TO	56	(INDEX 46)		
FLUID FLOW	45	FROM	55	TO	56	(INDEX 46)		
FLUID FLOW	46	FROM	56	TO	57	(INDEX 47)		
FLUID FLOW	47	FROM	57	TO	61	(INDEX 47)		
FLUID FLOW	48	FROM	61	TO	58	(INDEX 48)		
FLUID FLOW	48	FROM	58	TO	57	(INDEX 47)		
BEARING CONDUCTION	51	BETWEEN	6	AND	5	1.0000	1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	6	AND	7	1.0000	-1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	15	AND	14	2.0000	1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	15	AND	16	2.0000	-1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	21	AND	20	3.0000	1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	21	AND	22	3.0000	-1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	26	AND	25	4.0000	1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	26	AND	27	4.0000	-1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	33	AND	32	5.0000	1.0000	1.0000
BEARING CONDUCTION	51	BETWEEN	33	AND	34	5.0000	-1.0000	1.0000

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T E M P E R A T U R E   M A P

TEMPERATURES ARE IN DEGREES CELSIUS. THE FIRST 58 TEMPERATURES ARE CALCULATED, THE OTHERS ARE KNOWN

STEADY STATE TEMPERATURE CALCULATION, INITIAL TEMPERATURES

CALCULATED TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
1	75.000	2	75.000	3	75.000	4	75.000	5	75.000
6	75.000	7	75.000	8	75.000	9	75.000	10	75.000
11	75.000	12	75.000	13	75.000	14	75.000	15	75.000
16	75.000	17	75.000	18	75.000	19	75.000	20	75.000
21	75.000	22	75.000	23	75.000	24	75.000	25	75.000
26	75.000	27	75.000	28	75.000	29	75.000	30	75.000
31	75.000	32	75.000	33	75.000	34	75.000	35	75.000
36	75.000	37	75.000	38	75.000	39	75.000	40	75.000
41	75.000	42	75.000	43	75.000	44	75.000	45	75.000
46	75.000	47	75.000	48	75.000	49	75.000	50	75.000
51	75.000	52	75.000	53	75.000	54	75.000	55	75.000
56	75.000	57	75.000	58	75.000				

KNOWN BOUNDARY TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
59	75.000	60	24.000	61	70.000				

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

SHAFT GEOMETRY, BEARING LOCATIONS AND SHAFT LOAD. PLANE X - Y.

12 GEOMETRIC SECTIONS 1 LOAD SECTION(S), 5 BEARINGS. MODULUS OF ELASTICITY = 2.041+05

	POSI-TION	INNER DIAM. LEFT	INNER DIAM. RIGHT	OUTER DIAM. LEFT	OUTER DIAM. RIGHT	POINT FORCE	POINT MOMENT	LOAD INTENSITY LEFT	LOAD INTENSITY RIGHT		BEARING SEAT POS.ERR	BEARING SEAT DEFL/FOR	BEARING SEAT ANG.ERR	BEARING SEAT DEFL/MOM
1	.0	.0	65.4	.0	86.0					1				
2	13.0	65.4	65.4	86.0	86.0					2	.000	0.00	.0000	0.00
3	33.0	65.4	65.4	86.0	84.0					3				
4	40.0	65.4	65.4	84.0	84.0					4				
5	49.0	76.0	76.0	100.0	122.0					5				
6	58.0	92.0	92.0	124.0	124.0					6				
7	78.0	92.0	92.0	130.5	130.5	3800.0	318500.0			7				
8	104.0	92.0	92.0	139.0	139.0					8				
9	108.0	86.0	86.0	141.0	141.0					9				
10	112.0	78.0	78.0	96.0	96.0					10				
11	119.0	66.0	66.0	84.0	84.0					11				
12	122.0	64.0	64.0	84.0	84.0					12				
13	128.0	64.0	64.0	84.0	90.0					13				
14	148.0	64.0	64.0	90.0	90.0					14	.000	0.00	.0000	0.00
15	174.0	64.0	64.0	90.0	90.0					15	.000	0.00	.0000	0.00
16	200.0	64.0	64.0	90.0	90.0					16	.000	0.00	.0000	0.00
17	226.0	64.0	64.0	90.0	90.0					17	.000	0.00	.0000	0.00
18	239.0	64.0	.0	90.0	.0					18				

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

SHAFT GEOMETRY, BEARING LOCATIONS AND SHAFT LOAD, PLANE X - Z.

12 GEOMETRIC SECTIONS 1 LOAD SECTION(S), 5 BEARINGS. MODULUS OF ELASTICITY = 2.041+05

THRUST LOAD = 4.900+03

	POSI-TION	INNER DIAM. LEFT	INNER DIAM. RIGHT	OUTER DIAM. LEFT	OUTER DIAM. RIGHT	POINT FORCE	POINT MOMENT	LOAD INTENSITY LEFT	LOAD INTENSITY RIGHT		BEARING SEAT POS.ERR	BEARING SEAT DEFL/FOR	BEARING SEAT ANG.ERR	BEARING SEAT DEFL/MOM
1	.0	.0	65.4	.0	86.0					1				
2	13.0	65.4	65.4	86.0	86.0					2	.000	0.00	.0000	0.00
3	33.0	65.4	65.4	86.0	84.0					3				
4	40.0	65.4	65.4	84.0	84.0					4				
5	49.0	76.0	76.0	100.0	122.0					5				
6	58.0	92.0	92.0	124.0	124.0					6				
7	78.0	92.0	92.0	130.5	130.5	11600.0				7				
8	104.0	92.0	92.0	139.0	139.0					8				
9	108.0	86.0	86.0	141.0	141.0					9				
10	112.0	78.0	78.0	96.0	96.0					10				
11	113.0	66.0	66.0	84.0	84.0					11				
12	122.0	64.0	64.0	84.0	84.0					12				
13	128.0	64.0	64.0	84.0	90.0					13				
14	148.0	64.0	64.0	90.0	90.0					14	.000	0.00	.0000	0.00
15	174.0	64.0	64.0	90.0	90.0					15	.000	0.00	.0000	0.00
16	200.0	64.0	64.0	90.0	90.0					16	.000	0.00	.0000	0.00
17	226.0	64.0	64.0	90.0	90.0					17	.000	0.00	.0000	0.00
18	239.0	64.0	.0	90.0	.0					18				

IN STARFC/ROOT1
ROOT OF F(X) DOES NOT EXIST BELOW HO= .75000000+00

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

B E A R I N G S Y S T E M O U T P U T METRIC UNITS

	LINEAR (MM) AND ANGULAR (RADIANS) DEFLECTIONS					REACTION FORCES (N) AND MOMENTS (MM-N)				
BRG.	DX	DY	DZ	GY	GZ	FX	FY	FZ	MY	MZ
1	2.581-03	5.993-04	9.589-03	-3.579-05	5.621-05	0.000	459.	6.802+03	-318.	355.
2	2.581-03	7.524-03	1.205-02	3.314-06	3.545-05	2.389+03	670.	1.252+03	3.557+04	-1.834+04
3	2.581-03	8.370-03	1.188-02	8.389-06	3.025-05	2.380+03	769.	1.243+03	3.543+04	-2.128+04
4	2.581-03	9.109-03	1.162-02	1.129-05	2.709-05	2.410+03	868.	1.245+03	3.547+04	-2.405+04
5	2.581-03	9.780-03	1.129-02	1.370-05	2.472-05	-2.279+03	1.079+03	1.117+03	-3.104+04	3.071+04

	FATIGUE LIFE (HOURS)			H/SIGMA		LUBE-LIFE FACTOR		MATERIAL FACTOR	
BRG.	O. RACE	I. RACE	BEARING	O. RACE	I. RACE	O. RACE	I. RACE	O. RACE	I. RACE
1	2.594+05	2.009+05	1.221+05	1.05	.814	.455	.432	5.00	5.00
2	7.958+04	1.575+05	5.632+04	1.85	1.74	.639	.602	5.00	5.00
3	7.569+04	1.492+05	5.350+04	1.76	1.68	.611	.586	5.00	5.00
4	7.380+04	1.376+05	5.122+04	1.75	1.66	.607	.579	5.00	5.00
5	7.605+04	1.418+05	5.279+04	1.75	1.61	.607	.565	5.00	5.00

TEMPERATURES RELEVANT TO BEARING PERFORMANCE (DEGREES CENTIGRADE)

BRG.	SHAFT	I. RING	I. RACE	I. FLNG.	ROLL. EL.	O. FLNG.	O. RACE	O. RING	HSG.	BULK LUBE
1	116.	119.	118.	118.	115.	107.	107.	107.	103.	102.
2	78.7	82.3	82.3	82.3	86.5	85.0	85.0	85.0	86.2	78.3
3	79.6	84.6	84.6	84.6	94.3	88.1	88.1	88.1	87.4	84.8
4	80.1	85.3	85.3	85.3	94.6	88.4	88.4	88.4	87.3	85.1
5	82.0	87.3	87.3	87.3	95.3	88.4	88.4	88.4	86.5	86.0

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

B E A R I N G   S Y S T E M   O U T P U T   METRIC UNITS

FRICTIONAL HEAT GENERATION RATE (WATTS) AND FRICTION TORQUE (N-MM)

BRG.	O. RACE	O. FLNGS.	I. RACE	I. FLNGS.	R.E.DRAG	R.E.-CAGE	CAGE-LAND	TOTAL	TORQUE
1	1.033+03	0.000	405.	0.000	626.	20.5	10.4	2.096+03	1.472+03
2	266.	0.000	160.	0.000	293.	36.6	38.6	794.	557.
3	303.	0.000	194.	0.000	555.	32.1	34.3	1.118+03	785.
4	301.	0.000	195.	0.000	553.	31.5	34.1	1.115+03	783.
5	301.	0.000	190.	0.000	549.	31.1	33.5	1.104+03	776.

EHD FILM THICKNESS, FILM REDUCTION FACTORS AND HEAT CONDUCTIVITY DATA FOR THE OUTER AND INNER RACEWAYS RESPECTIVELY

BRG.	FILM (MICRONS)		STARVATION FACTOR		THERMAL FACTOR		MENISCUS DIST. (MM)		CONDUCTIVITY (W/DEG.C)	
1	.268	.207	.998	.959	.915	.932	.767	.225	18.5	9.18
2	.354	.332	.999	.993	.867	.869	1.16	.527	7.12	2.98
3	.337	.321	1.000	.998	.874	.875	1.69	.813	7.41	3.05
4	.335	.317	1.000	.998	.875	.876	1.69	.814	7.46	3.10
5	.335	.307	1.000	.998	.875	.880	1.69	.815	7.40	3.08

	FIT PRESSURES (N/MM2)				BEARING CLEARANCES (MM)			SPEED GIVING ZERO FIT PRESSURE
BRG.	SHAFT-COLD,	OPER.	HSG.-COLD,	OPER.	ORIGINAL	CHANGE	OPERATING	SHAFT-INNER RING (RPM)
1	10.5	8.41	0.000	0.000	3.800-02	-4.339-02	-5.390-03	3.390+04
2	6.63	3.37	0.000	0.000	2.053-02	-1.169-02	1.061-02	2.113+04
3	5.57	2.42	0.000	0.000	2.053-02	-1.126-02	1.104-02	2.021+04
4	5.57	2.38	0.000	0.000	2.053-02	-1.154-02	1.076-02	2.012+04
5	7.67	2.75	0.000	0.000	2.053-02	-1.508-02	7.222-03	1.851+04

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

B E A R I N G S Y S T E M O U T P U T METRIC UNITS

LUBRICANT TEMPERATURES AND PHYSICAL PROPERTIES

	LOCATION	TEMPERATURES (DEGREES C.)	DENSITY (GM/CM3)	VISCOSITY KINEMATIC (CS)	VISCOSITY DYNAMIC (CP)	PRESSURE VISCOSITY COEFFICIENT (MM2/N)
BRG. 1	OUTER	107.085	.8877	2.827	2.509	.9817-02
	INNER	117.977	.8800	2.433	2.141	.9235-02
	BULK	102.361	.8910	3.032	2.702	.1008-01
BRG. 2	OUTER	84.962	.9034	4.052	3.660	.1114-01
	INNER	82.322	.9052	4.255	3.852	.1131-01
	BULK	78.787	.9078	4.552	4.132	.1155-01
BRG. 3	OUTER	88.094	.9012	3.831	3.452	.1094-01
	INNER	84.629	.9036	4.077	3.684	.1116-01
	BULK	84.752	.9035	4.068	3.675	.1115-01
BRG. 4	OUTER	88.408	.9009	3.810	3.432	.1092-01
	INNER	85.257	.9032	4.030	3.640	.1112-01
	BULK	85.083	.9033	4.043	3.652	.1113-01
BRG. 5	OUTER	88.360	.9010	3.813	3.435	.1092-01
	INNER	87.273	.9017	3.887	3.505	.1099-01
	BULK	86.030	.9026	3.974	3.587	.1107-01

C A G E D A T A METRIC UNITS

	CAGE RAIL - RING LAND DATA				CAGE SPEED DATA					
BRG.	TORQUE (MM-N)	HEAT RATE (WATTS)	SEP.FORCE (NEWTONS)	ECCENTRICITY RATIO	EPICYCLIC SPEED (RAD/SEC)	EPICYCLIC SPEED (RPM)	CALCULATED SPEED (RAD/SEC)	CALCULATED SPEED (RPM)	CALC/EPIC RATIO	CAGE/SHAFT RATIO
1	-17.2	10.4	0.000	0.000	602.	5.749+03	602.	5.749+03	1.000	.423
2	49.1	38.6	1.618-03	1.000-02	638.	6.093+03	638.	6.093+03	1.00	.448
3	43.7	34.3	1.439-03	1.000-02	638.	6.097+03	638.	6.097+03	1.00	.448
4	43.4	34.1	1.430-03	1.000-02	638.	6.095+03	638.	6.095+03	1.00	.448
5	42.6	33.5	1.405-03	1.000-02	638.	6.095+03	638.	6.095+03	1.00	.448

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

ROLLING ELEMENT OUTPUT FOR BEARING NUMBER 1 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)				SPEED VECTOR ANGLES (DEGREES)		
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
.00	-4497.618	-.115	.000	4497.618	602.043	-180.00	180.00
22.50	-4497.618	-.143	.000	4497.618	602.043	-180.00	180.00
45.00	-4497.618	-.093	.000	4497.618	602.043	-180.00	180.00
67.50	-4497.618	-.076	.000	4497.618	602.043	-180.00	180.00
90.00	-4497.618	-.069	.000	4497.618	602.043	-180.00	180.00
112.50	-4497.618	-.017	.000	4497.618	602.043	-180.00	180.00
135.00	-4497.619	.021	.000	4497.618	602.043	180.00	180.00
157.50	-4497.619	.083	.000	4497.618	602.043	180.00	180.00
180.00	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
202.50	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
225.00	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
247.50	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
270.00	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
292.50	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
315.00	-4497.618	.000	.000	4497.618	602.043	180.00	180.00
337.50	-4497.618	.000	.000	4497.618	602.043	180.00	180.00

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 1 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
.00	.000	810.480	139.426	549.366	292.364	.3104	.6986	.00	.00
22.50	.000	1394.194	721.827	716.860	611.830	.2746	.4611	.00	.00
45.00	.000	1827.221	1255.991	826.604	802.054	.2556	.3885	.00	.00
67.50	.000	2299.878	1629.849	886.688	906.016	.2465	.3587	.00	.00
90.00	-.000	2404.899	1733.893	902.574	925.105	.2442	.3538	.00	.00
112.50	-.000	2208.612	1537.008	867.997	868.406	.2492	.3639	.00	.00
135.00	-.000	1763.491	1092.359	792.258	733.966	.2613	.4113	.00	.00
157.50	-.000	1209.142	538.345	663.845	524.562	.2849	.5061	.00	.00
180.00	-.000	671.137	.000	489.194	.000	.3258	.0000	.00	.00
202.50	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
225.00	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
247.50	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
270.00	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
292.50	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
315.00	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00
337.50	-.000	671.050	.000	489.162	.000	.3258	.0000	.00	.00

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 2 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)					SPEED VECTOR ANGLES (DEGREES)	
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
.00	-4157.256	729.758	-4.559	4220.823	624.693	170.04	-179.94
24.00	-4092.231	816.425	-5.046	4172.380	618.054	168.72	-179.93
48.00	-4057.495	866.523	-5.327	4148.995	614.807	167.94	-179.92
72.00	-4055.995	871.385	-5.361	4148.672	614.789	167.87	-179.92
56.00	-4087.756	832.483	-5.144	4171.667	617.959	168.49	-179.93
120.00	-4150.799	753.940	-4.708	4218.718	624.494	169.71	-179.93
144.00	-4235.714	652.725	-4.138	4285.714	633.924	171.24	-179.94
168.00	-4326.513	549.807	-3.545	4361.309	644.694	172.76	-179.95
192.00	-4406.380	462.386	-3.027	4430.575	654.648	174.01	-179.96
216.00	-4461.433	402.038	-2.660	4479.512	661.715	174.85	-179.97
240.00	-4481.668	376.864	-2.504	4497.486	664.311	175.19	-179.97
264.00	-4463.994	399.756	-2.580	4480.978	661.904	175.01	-179.97
238.00	-4411.415	439.990	-2.882	4433.304	654.992	174.30	-179.96
312.00	-4333.271	521.645	-3.365	4364.557	645.084	173.14	-179.96
336.00	-4242.902	624.210	-3.959	4288.575	634.236	171.63	-179.95

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 2 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
.00	-1.137	939.437	366.464	1108.148	994.248	.0403	.0590	11.67	31.24
24.00	-.483	1033.750	475.546	1144.056	1084.464	.0418	.0578	13.22	29.85
48.00	-.141	1106.363	555.072	1170.239	1141.828	.0426	.0572	14.13	29.11
72.00	.133	1111.429	560.478	1172.022	1145.523	.0426	.0571	14.22	29.16
96.00	.470	1046.267	488.566	1148.654	1094.272	.0418	.0577	13.49	29.97
120.00	1.103	954.615	382.946	1114.084	1008.935	.0404	.0588	12.07	31.42
144.00	2.686	878.690	286.328	1083.728	915.740	.0385	.0604	10.27	33.19
168.00	2.239	830.971	213.983	1063.744	831.019	.0366	.0624	8.49	34.93
192.00	.920	805.959	165.379	1052.963	762.625	.0350	.0644	7.03	36.33
216.00	.361	794.514	138.197	1047.954	718.519	.0335	.0660	6.04	37.23
240.00	.006	790.222	127.390	1046.064	699.083	.0330	.0666	5.64	37.50
264.00	-.347	790.853	133.796	1046.342	710.610	.0335	.0661	5.85	37.14
288.00	-.896	798.670	157.610	1049.778	750.490	.0349	.0647	6.68	36.18
312.00	-2.196	820.347	202.464	1059.191	815.831	.0365	.0627	8.05	34.73
336.00	-2.792	864.848	270.781	1078.008	898.856	.0384	.0607	9.81	32.99

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

ROLLING ELEMENT OUTPUT FOR BEARING NUMBER 3 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)				SPEED VECTOR ANGLES (DEGREES)		
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
.00	-4145.807	745.555	-4.649	4212.314	623.512	169.81	-179.94
24.00	-4082.802	830.626	-5.126	4166.442	617.180	168.50	-179.93
48.00	-4051.950	875.709	-5.380	4145.503	614.344	167.80	-179.92
72.00	-4055.339	874.166	-5.374	4148.490	614.775	167.84	-179.92
96.00	-4092.940	826.370	-5.111	4175.532	618.496	168.59	-179.93
120.00	-4162.112	739.763	-4.629	4227.345	625.699	169.92	-179.94
144.00	-4251.739	633.001	-4.024	4298.503	635.747	171.53	-179.95
168.00	-4345.053	527.399	-3.412	4376.945	646.928	173.08	-179.95
192.00	-4424.527	440.488	-2.894	4446.400	656.924	174.31	-179.96
216.00	-4476.445	383.461	-2.545	4492.840	663.640	175.10	-179.97
240.00	-4491.909	363.266	-2.418	4506.575	665.623	175.38	-179.97
264.00	-4468.208	382.808	-2.536	4484.577	662.419	175.10	-179.97
288.00	-4409.365	440.545	-2.884	4431.318	654.700	174.29	-179.96
312.00	-4325.977	529.303	-3.410	4358.239	644.176	173.02	-179.95
336.00	-4232.181	637.509	-4.036	4279.929	633.013	171.43	-179.95

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R O L L I N G   E L E M E N T   O U T P U T .FOR BEARING NUMBER 3 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
.00	-.881	953.357	383.103	1113.595	1009.074	.0497	.0669	11.95	31.02
24.00	-.374	1051.670	495.561	1150.628	1099.470	.0514	.0655	13.48	29.67
48.00	-.089	1119.976	569.970	1175.019	1151.953	.0522	.0647	14.29	29.02
72.00	.153	1113.026	562.317	1172.583	1146.775	.0521	.0648	14.26	29.17
96.00	.469	1036.771	478.141	1145.169	1036.433	.0511	.0656	13.38	30.11
120.00	1.090	941.507	367.442	1108.961	935.132	.0492	.0672	11.82	31.66
144.00	2.488	867.491	270.842	1079.104	898.924	.0467	.0694	9.93	33.49
168.00	1.710	823.458	201.421	1060.529	814.428	.0441	.0719	8.12	35.24
192.00	.720	801.272	155.231	1050.917	746.696	.0419	.0743	6.67	36.61
216.00	.270	791.714	129.515	1046.722	702.950	.0406	.0760	5.74	37.43
240.00	-.036	788.503	122.031	1045.305	689.140	.0402	.0766	5.42	37.63
264.00	-.360	789.969	131.479	1045.952	706.485	.0408	.0758	5.74	37.17
288.00	-.893	799.006	158.279	1049.926	751.552	.0424	.0740	6.69	36.12
312.00	-2.133	823.302	207.423	1060.462	822.439	.0447	.0715	8.18	34.59
336.00	-2.123	872.427	281.059	1081.148	910.088	.0473	.0690	10.04	32.78

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7/76

R O L L I N G   E L E M E N T   O U T P U T   FOR BEARING NUMBER 4 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)				SPEED VECTOR ANGLES (DEGREES)		
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
.00	-4131.371	765.431	-4.761	4201.682	622.041	169.50	-179.93
24.00	-4071.286	847.645	-5.222	4158.594	616.116	168.24	-179.93
48.00	-4044.746	887.042	-5.444	4140.875	613.727	167.63	-179.92
72.00	-4052.526	879.221	-5.403	4146.809	614.556	167.76	-179.92
96.00	-4094.882	824.709	-5.103	4177.108	618.719	168.61	-179.93
120.00	-4168.807	731.903	-4.585	4232.570	626.432	170.04	-179.94
144.00	-4261.743	621.306	-3.937	4306.796	636.310	171.71	-179.95
168.00	-4356.069	514.741	-3.337	4386.377	648.280	173.26	-179.96
192.00	-4434.212	429.304	-2.825	4454.946	658.157	174.47	-179.96
216.00	-4482.891	375.578	-2.496	4498.597	664.472	175.21	-179.97
240.00	-4493.250	360.741	-2.402	4507.709	665.785	175.41	-179.97
264.00	-4464.109	386.245	-2.556	4480.788	661.868	175.05	-179.97
288.00	-4400.283	450.012	-2.941	4423.235	653.532	174.16	-179.96
312.00	-4312.725	544.691	-3.500	4346.988	642.566	172.80	-179.95
336.00	-4217.164	656.545	-4.145	4267.967	631.325	171.15	-179.94

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R O L L I N G E L E M E N T O U T P U T FOR BEARING NUMBER 4 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
.00	-.775	972.367	405.483	1120.948	1028.352	.0511	.0693	12.30	30.73
24.00	-.325	1075.177	521.551	1159.136	1118.364	.0527	.0678	13.78	29.44
48.00	-.057	1139.245	591.409	1181.719	1166.219	.0534	.0671	14.50	28.88
72.00	.183	1120.253	570.595	1175.116	1152.374	.0532	.0673	14.35	29.13
96.00	.514	1033.236	474.339	1143.866	1083.545	.0520	.0683	13.35	30.17
120.00	1.185	934.246	358.868	1106.103	987.330	.0500	.0702	11.67	31.81
144.00	2.478	861.300	262.340	1076.531	889.418	.0473	.0726	9.73	33.68
168.00	1.491	819.498	194.393	1058.826	804.843	.0446	.0753	7.90	35.42
192.00	.638	799.179	150.072	1050.002	738.330	.0425	.0779	6.49	36.76
216.00	.225	790.856	127.007	1046.344	698.382	.0412	.0796	5.62	37.52
240.00	-.073	788.294	120.474	1045.213	686.197	.0410	.0800	5.38	37.63
264.00	-.407	790.584	132.496	1046.224	708.302	.0417	.0790	5.80	37.09
288.00	-.981	801.382	163.182	1050.965	759.233	.0435	.0769	6.85	35.96
312.00	-2.244	828.793	215.660	1062.814	833.184	.0459	.0742	8.44	34.35
336.00	-1.827	883.910	296.330	1085.870	926.281	.0487	.0715	10.38	32.50

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

R O L L I N G E L E M E N T O U T P U T FOR BEARING NUMBER 5 METRIC UNITS

AZIMUTH	ANGULAR SPEEDS (RADIANS/SECOND)				SPEED VECTOR ANGLES (DEGREES)		
ANGLE (DEG.)	WX	WY	WZ	TOTAL	ORBITAL	TAN-1(WY/WX)	TAN-1(WZ/WX)
.00	-4109.180	-786.567	4.873	4183.787	619.509	-169.16	179.93
24.00	-4058.058	-854.672	5.252	4147.086	614.462	-168.11	179.93
48.00	-4042.305	-874.342	5.359	4135.786	612.908	-167.80	179.92
72.00	-4061.716	-843.895	5.187	4148.461	614.606	-168.26	179.93
96.00	-4116.435	-765.722	4.747	4187.051	619.889	-169.46	179.93
120.00	-4200.041	-654.650	4.116	4250.756	628.783	-171.14	179.94
144.00	-4297.467	-535.014	3.425	4330.643	640.126	-172.90	179.95
168.00	-4390.275	-429.533	2.799	4411.238	651.711	-174.41	179.96
192.00	-4462.078	-353.696	2.338	4476.075	661.104	-175.47	179.97
216.00	-4500.408	-316.919	2.112	4511.553	666.268	-175.97	179.97
240.00	-4498.903	-322.719	2.150	4510.463	666.117	-175.90	179.97
264.00	-4457.174	-370.712	2.449	4472.565	660.621	-175.25	179.97
288.00	-4382.806	-454.362	2.958	4406.296	651.046	-174.08	179.96
312.00	-4288.106	-563.787	3.605	4325.011	639.390	-172.51	179.95
336.00	-4190.714	-681.961	4.284	4245.842	628.170	-170.76	179.94

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CH-53 POWER INPUT MODULE •STEADY STATE LUBRICATED ANALYSIS• 1450 SHP WP 7/76

R O L L I N G E L E M E N T O U T P U T FOR BEARING NUMBER 5 METRIC UNITS

AZIMUTH	NORMAL FORCES (NEWTONS)			HZ STRESS (N/MM**2)		LOAD RATIO QASP/QTOT		CONTACT ANGLES (DEG.)	
ANGLE (DEG.)	CAGE	OUTER	INNER	OUTER	INNER	OUTER	INNER	OUTER	INNER
.00	-.603	1001.440	439.386	1132.010	1056.249	.0516	.0777	-12.70	-30.08
24.00	-.237	1099.944	548.964	1167.971	1137.624	.0529	.0760	-13.94	-28.87
48.00	.007	1138.889	591.176	1181.596	1166.066	.0533	.0755	-14.30	-28.43
72.00	.254	1088.123	535.969	1163.772	1128.576	.0529	.0762	-13.76	-28.82
96.00	.634	984.538	421.227	1125.605	1041.493	.0514	.0780	-12.35	-30.00
120.00	1.479	887.655	304.463	1087.402	934.679	.0491	.0807	-10.39	-31.74
144.00	2.427	824.999	215.543	1061.190	833.033	.0463	.0841	-8.32	-33.63
168.00	1.158	793.150	156.015	1047.334	747.951	.0436	.0876	-6.55	-35.33
192.00	.492	780.512	120.871	1041.762	686.951	.0417	.0905	-5.32	-36.59
216.00	.136	777.526	105.305	1040.432	656.096	.0407	.0921	-4.73	-37.27
240.00	-.154	779.264	108.543	1041.206	662.753	.0407	.0920	-4.81	-37.30
264.00	-.519	785.659	128.047	1044.047	700.284	.0418	.0901	-5.58	-36.67
288.00	-1.218	802.022	168.134	1051.245	766.836	.0438	.0871	-6.94	-35.44
312.00	-2.449	837.440	230.290	1066.497	851.614	.0465	.0836	-8.78	-33.74
336.00	-1.399	903.533	322.133	1093.847	952.422	.0493	.0803	-10.84	-31.83

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CH-53 POWER INPUT MODULE *STEADY STATE LUBRICATED ANALYSIS* 1450 SHP WP 7 76

T E M P E R A T U R E   M A P

TEMPERATURES ARE IN DEGREES CELSIUS. THE FIRST 58 TEMPERATURES ARE CALCULATED. THE OTHERS ARE KNOWN

STEADY STATE TEMPERATURE CALCULATION. FINAL RESULT AFTER 6 ITERATIONS

CALCULATED TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
1	93.103	2	94.718	3	80.748	4	115.494	5	117.314
6	113.694	7	106.140	8	102.353	9	107.245	10	106.375
11	95.107	12	101.027	13	78.735	14	82.319	15	86.455
16	84.951	17	86.153	18	88.457	19	79.555	20	84.628
21	94.332	22	88.084	23	87.388	24	80.050	25	85.253
26	94.609	27	88.333	28	87.313	29	86.495	30	79.623
31	81.989	32	87.267	33	95.328	34	88.343	35	86.504
36	85.144	37	103.561	38	84.396	39	83.695	40	92.442
41	101.703	42	72.266	43	78.785	44	90.902	45	72.494
46	84.750	47	94.703	48	72.632	49	85.078	50	95.285
51	73.183	52	86.022	53	95.677	54	95.415	55	95.130
56	93.922	57	101.778	58	87.757				

KNOWN BOUNDARY TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
59	75.000	60	24.000	61	70.000				

@FIN

RUNID: CH53WT ACCT: 8016P2801 PROJECT: TRANS

TIME: TOTAL: 00:08:37.675 COST: 21.68

CPU: 00:07:43.388 I/O: 00:00:35.518

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